A CRITICAL REVIEW AND SIMULATION-BASED EVALUATION OF GREEN ROOF'S ENERGY SAVINGS

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A CRITICAL REVIEW AND SIMULATION-BASED EVALUATION OF GREEN ROOF'S ENERGY SAVINGS

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LIST OF SYMBOLS AND ABBREVIATIONS

CBA	Cost-benefit Analysis
DOE	Department of Energy
ERU	Equivalent Runoff Unit
EUI	Energy Use Intensity
GA	Genetic Algorithm
GPS	Generalized Pattern Search
IEAD	Insulation Entirely above Deck
LAI	Leaf Area Index
PM	Particulate Matter
PSO	Particle Swarm Optimization
RC	Reinforced Concrete
UHI	Urban Heat Island

SUMMARY

Global energy demands and carbon emissions have registered a sharp rise in the past two decades, which can be mainly attributed to various economic sectors like transportation, industry, and buildings. The building sector contributes about 42% of the total energy consumption of the world. A number of researches have been, thus, carried out which could provide scientific and feasible solutions to growing environmental issues caused by this sector. Implementing a green roof is one such field of research that has been explored extensively because of the several benefits it provides.

A widespread recognition and growing literature of simulated and empirical data exist for various building typologies that suggests that green roofs improve building energy efficiency through its various mechanisms. A comprehensive literature review carried out in this research shows significant energy saving figures ranging from 12 to 60%.

On the contrary, a simulation study on green roofs conducted in this research presents insignificant energy-saving figures. The results of this research give a major insight into the thermal performance of a green roof based on insulation thickness. It was observed that the insignificant results were due to high R-values of the original roof assembly. This study, therefore, performs optimization to obtain the best set of green roof design parameters that could maximize its energy savings on a well-insulated conventional roof. But the optimization was only able to achieve maximum energy savings ranging from -0.17 to 5.77%. With marginal energy savings figures, green roofs may be perceived as a costly investment with high installation and operation costs.

However, a cost-benefit analysis of green roofs shows that the other numerous benefits of green roofs such as carbon sequestration, improved air quality, reduction of noise pollution, pleasing views and aesthetics increase property value and contribute significantly to the lesser-known economic benefits. After combining the net present value of the entire time frame, green roofs seem to be not only feasible but also a lucrative option for the numerous benefits it provides both at the private and public level. This research thus presents the other more beneficial aspects of green roofs as key factors in establishing it as a sustainable measure. It discusses an outlook beyond the cost comparison, as green roofs can outperform conventional roofs from an ecological and social point of view.

A sensitivity analysis is also carried out in this study to assess the significance of various green roof design parameters such as the Leaf Area Index, Plant Height, Leaf Reflectivity, Leaf Emissivity, Soil Depth & Minimum Stomatal Resistance which will help in designing a green roof based on the climate zone to achieve maximum energy savings.

CHAPTER 1. INTRODUCTION

The ever-increasing global population has led to intensive urbanization and it has been estimated that by 2050, the percentage of urban population will reach 66% (Floater, et al., 2014). This trend has led to a surge in urban temperature and is one of the major contributors to climate change. A large percentage of global energy demands and carbon emissions can be attributed to the building sector (La Roche & Berardi, 2014). Many sustainable practices have therefore evolved as remedial measures to solve these serious environmental issues.

Green Roofs have been presented as one such sustainability design measure which can help in mitigating the above-posed problems. A significant amount of published literature exists which has investigated the thermal performance of a green roof under various climatic conditions. Most of the studies advocate its usage to enhance energy savings in a building. A study carried out on a five-story commercial building in Singapore shows an annual energy reduction of 29 MWh (Wong N. H., et al., 2003). In another study, the thermal load of a building was found to be reduced by 60% in an experimental setting of an extensive green roof in the Mediterranean climate zone (Olivieri, Di Perna, D'Orazio, Olivieri, & Neila, 2013). Yet another research shows a 32% reduction in annual energy consumption in a single-family house for the climate of Athens, Greece (Jaffal, Ouldboukhitine, & Belarbi, 2012). A study carried out by Kotsiris, G., et al. discards the view presented by some known researchers that green roofs don't have a significant contribution to energy reduction on well-insulated roofs. It further states that green roof systems with different substrate composition and depths can produce energy savings for cooling ranging between

11.8-15.45% (Kotsiris, Androutsopoulos, Polychroni, & Nektarios, 2012). A study aimed at investigating thermal behavior comparisons of different roof typologies such as cool roof, green roof, and conventional roof shows the heating and cooling energy reductions reaching as high as 36.91% and 85% (Gagliano, Detommaso, Nocera, & Evola, 2015). Another experimental investigation that examined energy savings by the installation of a green roof on a nursery school building in Athens, approached the problem mathematically and calculated the cooling and heating load. The study shows a significant reduction in the cooling energy ranging from 6% to 49% for both the insulated and non-insulated rooftops whereas the influence of green roof on heating load was found insignificant (Santamouris, et al., 2007).

All the above studies displayed quite encouraging results of energy savings by green roofs. These results served as a motivation to carry out a simulation study to quantify the thermal performance of green roofs. But the simulation study showed contrasting results when compared with the above findings. These contrasting results were due to the high R-value of the base roof assembly which brought into notice the significance of a key parameter, insulation thickness, which significantly impacts a green roof's performance. This study, thus, provides an insight into the energy savings potential of green roof based on the insulation of a building and proposes that they are not effective measures for reducing energy consumption if the base roof is well insulated and has a high R-value. Therefore, their deployment should be assessed based on not just their energy savings feature, but their other beneficial aspects such as improved air quality, carbon sequestration potential, storm-water management, and reduction of urban heat islands.

1.1 Research Gap

Green roofs are often identified as energy-efficient techniques which, through their various mechanisms, contribute to a comfortable indoor environment. A significant number of published literature has investigated the thermal performance of a green roof under various climatic conditions and building parameters. But most of the reviews, which focus on the energy impacts of a green roof, were found misleading in terms of its energy improvement potential. Thus, the identified research gap is the low prospects of a green roof in reducing energy consumption on a well-insulated roof assembly.

1.2 Research Goal

This thesis investigates the existing literature which claims significantly high figures of thermal load reduction by green roofs, to study the settings under which the experimental and simulation studies were carried out which led to high energy savings. The work aims to verify the feasibility of a green roof, especially the energy savings aspect, by taking into consideration all the factors which affect its thermal performance.

1.3 Research Objectives

- Comparison of energy consumption data of a reference building under two conditions: 1) With green roof installation 2) With a reference non-vegetated roof. The comparison will help in the thermal evaluation of the green roof.
- Identification of research papers that present inflated figures of energy savings by scarcely mentioning the thermal properties of insulation and the other related factors and documenting their experimental settings.

- Optimization of green roof installation input parameters that define the thermal performance of green roof assembly. An appropriate optimization algorithm is to be used to reach optimal energy savings. The design space will be kept under control using selective inputs from the domain.
- Demonstration of a Cost-Benefit Analysis (CBA) of a green roof, and conversion of benefits other than energy savings into a monetary unit to better reflect their economic potential.

1.4 Research Significance

This study's innovation is the focus on demonstrating the energy savings potential of green roofs as compared to the traditional insulation of a building. Contemporary codes and standards for building insulation mandate compliance to recommended insulation values that are typically high enough to have thermal efficiency approximately equal to or greater than provided by a green roof. Considering their high installation, operation, and maintenance costs, the average payback period with a comparably small amount of savings is considerably high.

1.5 Research Hypothesis

Are green roofs a justifiable investment, considering their high initial installation and operation cost and very low energy savings? With other numerous social and environmental benefits, can green roofs be considered as an economically feasible strategy for a building?

1.6 Thesis Overview

The first chapter forms the context of this study and describes the research goals and objectives. The literature review served as the first step towards carrying out this study which helped in exploring the mechanism of green roof systems, the factors impacting its thermal efficiency, and numerous benefits. The findings of the literature review have been presented in Chapter 2. This was followed by the identification of the research papers which specifically focused on the energy performance to gain insights on the energy savings potential of green roofs. The third chapter shows the documents and settings of all the identified papers which represented inflated figures of energy savings, with the factors singled out which caused such high figures. The fourth chapter demonstrates the methodology of carrying out the simulation study using optimization for obtaining the best solution of green roof parameters which maximize the energy savings. It presents the baseline conditions and simulation settings. It also explains the procedure for carrying out the cost-benefit analysis of green roofs. The fifth chapter illustrates the results of the experiment. The sixth and final chapter discusses the results and the future scope of the study. Figure 1 describes the comprehensive research workflow.

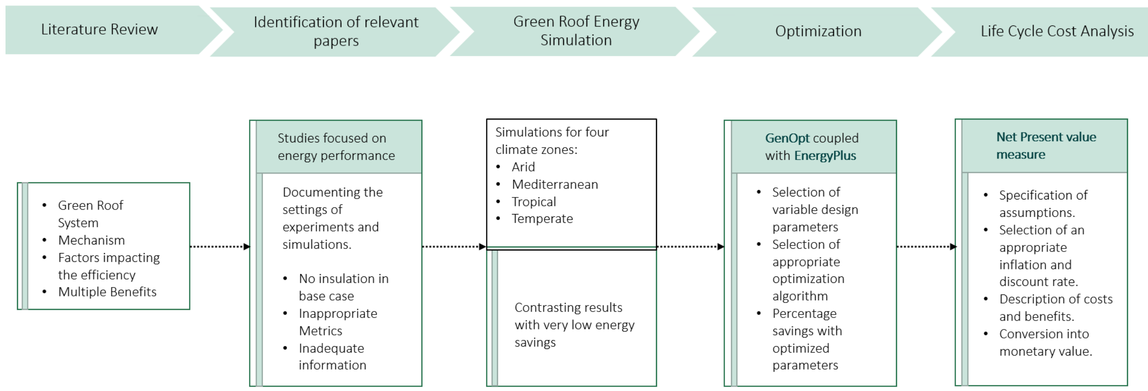


Figure 1 - Research framework

CHAPTER 2. LITERATURE REVIEW

This chapter investigates the literature related to a green roof, with respect to its typologies, benefits, component layers, and factors impacting its thermal efficiency. It also aims to gain thorough insights into the optimization process and related algorithms, which will be used for optimizing green roof parameters to maximize energy-savings.

2.1 Green Roofs

A green roof is a living system in which a significant portion of the roof is covered with lightweight vegetation. The layers between the roof structure and the growing media vary depending on the design and generally consist of a root barrier, waterproofing, irrigation, and drainage layers (Castleton, Stovin, Beck, & Davison, 2010). Green roofs can be classified depending on the thickness of the substrate. Roofs with the depth of the vegetative layer varying from 20 to 80 cm are known as intensive green roofs (Zhang, Shen, Tam, & Lee, 2012). With deeper soils, it is capable of supporting large trees and shrubs. Large soil depths lead to high structural loading & more water retention capacity. Hence they require a rigorous maintenance schedule (Berndtsson, Bengtsson, & Jinno, 2009). Semi-Intensive green roofs are characterized by small herbal plants of depth varying from 12-20 cm & they require occasional maintenance. Extensive green roofs, on the other hand, have thinner implementations of less than 20 cm depth and provide limited options of plant species. These roofs are quite lightweight and reduce the irrigation need. The structural requirements for these roofs are less complex and they can be installed on sloped surfaces (Zhang, Shen, Tam, & Lee, 2012) (Shafique M. K., 2018).

2.1.1 Green Roof Benefits

Green Roofs provide a broad range of benefits. The thermal properties of a green roof vary from a conventional roof because of the presence of plants, soil, and water (Becker & Wang, 2013). They help in attaining lower surface temperature due to the process of evapotranspiration, thus producing cooling effects. Temperature reductions, in turn, aid in decreasing energy demands. Earlier studies show that the peak surface temperature (roof membrane) drop from 66ºC to 32ºC was observed with the installation of a green roof on a community center building in Toronto (Liu, 2005). A previous study suggests that they can aid in decreasing heating loads over non-insulated roofs, ranging from 20 to 60% in various climate zones. Whereas cooling energy demand can be reduced up to 70% by employing a non-insulated green roof in a dry climate with hot summer (Susca, 2019). They help in improving air quality by absorbing carbon dioxide and filtering pollutants. Nearly 85 kg of air contaminants can be filtered annually by a green roof spread over a hectare (Chen, 2015). Apart from this, they also help in reducing storm-water runoff by capturing water from precipitation, thereby effectively managing storm drain systems. These roofs are known to reduce the peak runoff by approximately 65% and can extend the holding capacity by 3 hours (Sproul, Wan, Mandel, & Rosenfeld, 2014). Noise issues in the urban environment form a major challenge, which can be tackled by increasing green roof coverage. Especially in airport surroundings, the multi-layered system of green roofs helps in reducing sound reflection & improves the sound insulation properties. (Van, 2018). Also, the lifespan of a green roof is greater than the conventional roofing system, as the vegetation layer shields the inner membrane from extreme weather conditions (Liu, 2005). Extensive green roof systems have a life span of 25 years which is almost twice the age of a conventional roof (Kosareo & Ries, 2007). They also enhance the built environment with their aesthetically pleasing view.

2.1.2 Green Roof Mechanism for Enhancing Thermal Performance

Green roofs enhance the thermal performance of a building through various mechanisms:

- Shading: the top vegetative layer of the green roof shades the underlying roof assembly by blocking solar radiation.

- Evapotranspiration: processes of transpiration in plants and evaporation in soil, cool the surface by removing the heat.

- Thermal Inertia: various layers of green roof add to the thermal mass, thus increasing the heat resistance by delaying the heat flux. (Cascone, 2019)

2.1.3 Green Roof Component Layers

To match up the long term design intent of a green roof in the context of a specific building, green roofs are formally engineered and designed, depending on the location, building configuration, load capacity, and needs of the user (Vijayaraghavan, 2014). Figure 2 shows the constituent layers of a green roof. Each green roof component plays an important part in its performance and its design is influenced by the above-mentioned factors.

a) Vegetative Layer: Plants constitute the topmost layer of the system. They exhibit different behavior in different seasons. Vegetation specifications such as Leaf Area Index

(LAI), height, fractional coverage, and stomatal resistance, play a significant role in influencing the evapotranspiration rates and heat transfer process through green roofs (Sailor, 2008). The thermal behavior of various plant species has been simulated under different climatic conditions. Vegetative species are also selected for their reflectance. Although it is difficult to select a plant species showcasing all favorable characteristics, much research has been pursued to identify the most suitable vegetation. Native species are generally considered ideal for green roof landscape as they can easily adapt to the local climates (Oberndorfer, et al., 2007). For extensive green roofs, Sedum species are the most preferred and considered positively yielding because of their ability to survive drought conditions (Butler & Orians, 2011). The morphological characters such as LAI, canopy coverage and, root density vary across different species & they govern the water use, evapotranspiration rate, CO_2 exchange rates, and various other metabolisms that occur during the process of photosynthesis.

b) Growth Substrate: Characteristics of growing mediums have a direct influence on plant growth and they impact the thermal performance of green roofs. Several mineral-based components are mixed in definite proportion to constitute the growing media. It constitutes the major load of green roofs on the structure. Hence the weight of the substrate should be kept minimal. The water retention capacity of the components is important for the survival of plants under drought conditions and also in managing stormwater flow in peak seasons. The thermal insulation provided by the soil layer in cold regions can play a crucial role in decreasing heating loads (Susca, 2019). In addition to that, aeration and flow properties of the substrate helps in preventing roof leakage as they improve the water retention capacity (Vijayaraghavan, 2014) (Friedrich, 2009) (Getter & Rowe, 2006). Therefore, the growing substrate should be properly engineered to optimize the above factors to maximize the green roof benefits.

c) Filter Layer: The filter layer functions to keep the vegetative layer and growing media intact. This layer prevents the infiltration of fine materials to the layers below during the draining process (Vijayaraghavan & Raja, Pilot-scale evaluation of green roofs with Sargassum biomass as an additive to improve runoff quality, 2015). It forms an intermediate layer between the growing media and the drainage layer. The filter fabrics in this layer inhibit the movement of substrate particles, allowing the water to percolate at the same time. Also, this fabric is tensile in nature to withstand the load of the upper layers of vegetation and growing media (Bianchini & Hewage, 2012).

d) Drainage layer: This layer helps in the removal of excess water if any, thereby ensuring an aerated state of the substrate required for proper plant growth. It helps in providing an ideal balance of air and water in the green roof. It alleviates the risk of water leakage through the assembly. Drainage modular panels made up of high strength plastic materials are suitable for large scale installations of green roofs and are suitable for sloped surfaces as well (Bianchini & Hewage, 2012). In certain designs, a water retention layer, commonly known as moisture mats is also installed above the filter layer to retain moisture in the growing media, thus reducing the impact of early-stage drought.

e) Waterproofing and Root Barrier layer: It is the first layer just next to the building roof assembly and acts as a waterproofing membrane. It protects the roof structure from the possible penetration of the roots which can cause cracks and holes in the base roof (Bianchini & Hewage, 2012).

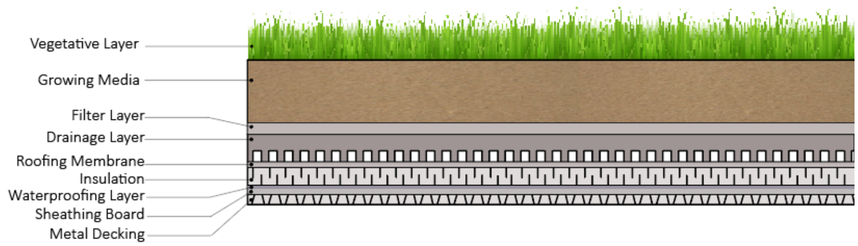


Figure 2 - Green roof component layers (Center for Watershed Protection, Inc., 2020) *Reproduced*

2.1.4 Factors impacting green roof efficiency

Apart from the constituting layers and their characteristics influencing the performance of green roofs, there are other parameters that govern the thermal behavior of green roofs.

a) Building Typology: Green roofs can be installed in both existing buildings as well as new construction. Intensive roofs are generally installed when the slope is less than 10 degrees whereas extensive roofs can be implemented on a larger slope and large-sized rooftops. The selection of a suitable drainage layer will also depend on the roof slope. Special precaution is needed in the case of sloped vegetative roofs to prevent the substrate from slipping off due to storm runoff and the load of the green roof in general (Cascone, 2019).

b) Climatic Impact: Green roofs cannot serve as a universal solution for decreasing the energy demands of buildings in diverse climates. Previous investigations revealed that green roofs can be more favorable in climates where heating loads are dominant (Susca, 2019). Relative humidity and intensity of solar radiations are two key parameters that determine the cooling potential of the green roof via evapotranspiration. In humid climates, the rate of evapotranspiration decreases making the green roof, less effective as compared to hot and dry climates. The reduction of cooling demand and thermal comfort are more pronounced when the climate is hot. But a significant reduction in the heating demand can also be observed in cold climates. Green roofs are the least efficient in temperate climates which are characterized by low solar radiations and high relative humidity such as the south and middle east coasts of the United States(Morakinyo, Dahanayake, Ng, & Chow, 2017). High values of wind speed enhance the evaporation rate and thus the cooling capabilities of a green roof. Not only this, but environmental conditions such as the amount and distribution of rainfall and temperatures also play a major role in determining plant species and determine irrigation needs (Getter & Rowe, 2006).

c) Insulation thickness: Several investigations have been carried out in the past to study the effect of insulation at varied thicknesses. The outcomes of these studies suggested that a non-insulated green roof is beneficial in the cooling season but is less favorable in the winter season. A green roof provides passive cooling effects of evapotranspiration and helps in reducing the cooling loads of a building. Heat is removed from the interior of the building by a wet green roof via evapotranspiration as it is coupled with the indoor building environment. The detailed mechanism includes the heat exchange between the roof surface & the inside of the building. A higher insulation value would decouple the building interior from the outdoor environment and thus hamper the ability of the green roof to remove heat from the building during the cooling season. The same insulation would be beneficial for the heating season as the heat would be trapped inside by a lower U-value of the roof. Thus, to accommodate both the benefits, it has been suggested by a previous study that a variable insulation system integrated with green roofs would allow the extension of the applicability of green roof benefits beyond particular seasons (La Roche & Berardi, 2014).

d) Roof-Envelope Ratio: Previous studies demonstrate that for smaller roof-envelope ratios, a green roof does not prove to be beneficial. On the other hand, they provide significant energy savings over conventional roofs with increased roof envelope ratio (Martens, Bass, & Alcazar, 2008). A low height building with a high roof-to-wall ratio would benefit more than a high rise building, as the latter loses more energy through its envelope (Weiler & Scholz-Barth, 2009).

An extensive study of the green roof literature provided some useful understanding of its component layers and the design parameters which significantly affect its thermal performance. It established the foundation for performing the energy simulations along with the optimization, by keeping the key impact factors under consideration. The following section presents the literature review of the optimization model & algorithms, that were adopted in this research for improving the green roof design to achieve maximum energy savings.

2.2 Optimization

Optimization is the process that aims to find the best solution of a function under given constraints. In the design process, various available design solutions are compared to each other, to achieve optimal performance defined by one or more competitive objective functions. A variety of tools are available to identify the best trade-offs and determine a set of parameters that satisfy more than one goal, often contrasting (Bertsimas, 2009).

2.2.1 Terminologies

Cost Function/Objective Function: The function which is used to evaluate the design performance using variable values. The optimization problems deal with finding numerically maximum or minimum of these functions. The objective function can be single-objective or multi-objective (Rothlauf, 2011). Mathematically, the objective function can be represented as:

$$maximise\ or\ minimize\ f(x1, x2)$$

$$subjected\ to\ x1, x2 \in X\ where\ X \in Rn$$

Decision Variables: The variables whose values are changed over the specified constraints to maximize or minimize the objective function. In the above representation, $x1$ and $x2$ are decision variables (Rothlauf, 2011).

Feasible Region: Also known as the constraint region, the feasible region represents the extent to which the values of the decision variables are varied, thus it gives the set of alternatives of the decision variables for which the objective function needs to be optimized. In the above representation, set *X* shows the feasible region (Rothlauf, 2011).

Optimal Solution: The values of the decision variables which help in achieving the minimum or maximum of the objective function over a feasible region. (Rothlauf, 2011).

2.2.2 Optimization Algorithms

The selection and performance of an appropriate optimization algorithm are crucial in finding an effective solution to a given problem. These algorithms are the methods and techniques used to solve an optimization problem. The efficiency of the algorithm mostly depends on the complexity of the proposed problem. There are no set regulations and recommendations for choosing an algorithm for a particular problem, also there is no universal algorithm that is appropriate for all types of problems; though, there have been various empirical observations from previous researches (Kochenderfer & Wheeler, 2019). Various optimization algorithms exist based on the type of problem we are trying to solve, their nature of randomness, and the preferred quality of the solution. Sometimes the usage of a particular algorithm is limited by time constraints and computational resources. GenOpt, a generic optimization program, has a library of multiple optimization algorithms such as Hooke-Jeeves, Coordinate Search Algorithm which are based on generalized pattern search methods, Discrete Armijo Gradient algorithm, Particle Swarm Optimization, Nelder Mead which are examples of multi-dimensional optimization (Wetter M. , 2016). Multi-dimensional optimization performs by solving a one-dimensional optimization problem in a different search direction in the successive iterations. One dimensional optimization algorithms were kept out of the scope of this study since they were inefficient for the proposed problem (Brent, 1973). A brief description of these optimization algorithms has been given in the following subsections. Optimization algorithms can be classified in several ways based on different criteria. Based on the randomness of their nature, they can be divided into Deterministic or Stochastic. A deterministic algorithm will always produce the same result with the same input value in every iteration, by undergoing the exact same stages in the entire process. Stochastic algorithms are more random in nature. The result of these algorithms is not uniquely defined in each run, even with the same input value. They reach a different solution for the same starting point and exhibit different behavior for each run. Deterministic algorithms can be further divided into Direct methods (zero-order methods) or Gradient-based methods (of 1st and 2nd order). Direct methods are derivative-free and use the value of the proposed objective function to find the optimal solution. Generalized Pattern Search Methods (i.e. the Coordinate search and the Hooke Jeeves) and the Nelder Mead Simplex Method come under the category of Direct methods. Gradient methods use the derivatives of the objective function to reach a solution. Discrete Armijo algorithm is an example of gradient-based methods. Evolutionary or genetic algorithm and Particle swarm optimization algorithm are identified under stochastic methods since they are population-based. The randomness that these stochastic algorithms employ can be singled out when they are analyzed in detail based on where the randomness is introduced (Yang, 2013) (Wetter, 2004) (Zakharova, 2015) (Wetter M. , 2016). Though many other promising algorithms exist which could be classified in these categories and other subheads based on different criteria, only limited types of algorithms were studied which were in the library of the GenOpt program and were relevant to the current study.

2.2.2.1 Coordinate Search Algorithm

This algorithm helps in achieving the optimal solution for the proposed problem by solving a series of scalar mini-problems. The search begins with initially selected coordinates or sets of variables and the function is tried to optimize with respect to that 1st variable by keeping all the other coordinates fixed. After solving the initial one, the next coordinates are optimized iteratively, one at a time. It involves a series of line searches, along with a set of n variables ($x1, x2, x3 \ldots\ldots xn$) for a multivariable function F(X). If there is no improvement after a full search in each coordinate direction ($X0, X1, X2\ldots\ldots$) this implies that the method has converged. (Li & Osher, 2009) (Kochenderfer & Wheeler, 2019)

$$\mathrm{F}(X) = f(x1, x2, x3 \ldots\ldots..xn)$$

$$Initial\ Coordinates\ X0 = (x10, x20, x30, \ldots\ldots..xn0)$$

$$When\ 1st\ input\ is\ minimized\ X1 = \arg\min\ \mathrm{f}(x1, x20\ , x30\ldots, xn0\ )$$

$$The\ next\ iteration\ would\ solve\ in\ the\ direction\ of\ X2 = \arg\min f(x10, x2, x30, \ldots\ldots xn0)$$

$$Also\ F(X0) > F(X1) > F(X2) \ldots\ldots\ldots..$$

2.2.2.2 Hookes Jeeve Algorithm

A part of the Generalized Pattern Search (GPS) method, this algorithm improves upon the solution of the objective function by specifying the searching direction as the process moves from one point to the other rather than starting over with a new point in each iteration. It's a series of exploratory moves which starts with an initial base point and finds the next point by hit and trial. If the value of the objective function at the trial point is less than the value at the initial point, the step is considered successful. Also, if no improvements are found the step size is reduced and the algorithm keeps on running until the step size decreases to a sufficiently small value. After the search is complete along the possible coordinate directions, the newly reached point term is now termed as the base point and the process is followed by a pattern search. The pattern search makes use of the previous information acquired to reach the current base point in order to speed up the next point search. Since the last search direction led to the decrease in the value of the objective function, it tries to find the new point based on that pattern. This algorithm work specifically for continuous design variables (Weisman & Gottfried, 1973) (Kirgat & Surde, 2014) (Zakharova, 2015). The new point with pattern search is given by the equation:

$$\mathrm{Xp} = xk + \mu(xk - x(k-1))$$

$where$ Xp: $New\ point\ \ obtained\ during\ the\ pattern\ search$
xk: $Current\ base\ point$
x(k-1) : Preceding base point

2.2.2.3 Simple Genetic Algorithm

The mechanism of genetic algorithm mimics the concept of natural selection and the principle of the survival of the fittest plays a major role in this selection process. This algorithm works on an initial set of points (chromosomes) called population which is a pool of possible solutions to the given optimization problem. The fittest chromosomes or the solutions which mostly fit the desired value of the objective function are chosen for reproduction in the process of natural selection. The least adapted solutions are removed from the population. The most fitted or adapted solutions then undergo crossover and random mutation to produce a new generation of more evolved populations. The process is repeated over generations to produce a fitter set of solutions. The stochastic nature of this algorithm can be observed in the initial set of population, which is random in nature. Apart from this, it also uses randomness in the recombination and mutation. A simple GA is run for a user prescribed number of generations (Zakharova, 2015) (Yang, 2013) (Wetter & Wright, Comparison of a generalized pattern search and a genetic algorithm optimization method., 2003).

2.2.2.4 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a population-based stochastic algorithm, which can work for both continuous and discrete independent variables. Its computation mechanism is similar to the genetic algorithm in certain aspects and is inspired by the observed behavior of animals such as bird flocks or fish schools. The main idea behind this algorithm is to create a swarm of potential solutions that move in the search space to find a location or the optimal solution that best fits with the desired criteria of the objective function. The algorithm is initialized by a random generation of a potential set of solutions called particles. These sets of particles in each iteration are termed as population. The initial velocity is assigned to these particles stochastically to provide the required momentum to the particles for extensive exploration of the problem space. The fitness value of these particles is evaluated by the objective function of the problem. The particles update their location and velocity in each iteration. The velocity of the particles in each dimension of the search space is adjusted after combining the particle information together in each iteration, which further helps in computing the new location of that particle. The updated location of each particle in the next iteration is determined by the social behavior of the swarm. The swarm behavior is governed by two values called pbest and gbest. The best value that a specific particle has achieved so far until the current iteration based on the fitness of the objective function is called pbest. The best solution that any particle has achieved in the population is called "gbest" or global best. The particles update their location in each iteration based on the direction of their pbest and gbest locations in the swarm. Iterations are repeated until an optimal solution is reached or the algorithm reaches a stopping criterion (Pereira, 2011) (Zhang, Wang, & Ji, 2015) (Kennedy & Eberhart, 1995) (Wang, Tan, & Liu, 2018).

$$\mathrm{Vi}\ (\mathrm{t}+1) = \omega \mathrm{Vi}\ (\mathrm{t}) + \mathrm{c1r1}\ \big(\mathrm{pbest(i,t)} - \mathrm{Pi}\ (\mathrm{t})\big) + \mathrm{c2r2}\ \big(\mathrm{gbest(t)} - \mathrm{Pi}\ (\mathrm{t})\big),$$
$$\mathrm{Pi}\ (\mathrm{t}+1) = \mathrm{Pi}\ (\mathrm{t}) + \mathrm{Vi}\ (\mathrm{t}+1)$$

Where Vi: velocity of particle i in dimension d;
i: index of the particle
t: iteration number
c1: acceleration coefficients for the cognitive component
c2: acceleration coefficients for the social component
r1,r2: stochastic component of the algorithm, a random value between 0 and 1
ω: inertia weight
P: position

2.3 Identification of Relevant Papers

The following research papers were taken as reference studies in the literature review. A thorough study of each of these papers helped in understanding the conditions and the settings under which these studies were performed and which contributed to producing large energy-saving figures. These factors have been singled out to provide support to the contrasting results produced in this study.

1) The effects of rooftop garden on energy consumption of a commercial building in Singapore (Wong N. H., et al., 2003): The paper studied the effects of a green roof on annual energy consumption and cooling load on a five-story hypothetical commercial building in Singapore. It was expected that Singapore, being warm and humid would experience very less energy savings due to less rate of evapotranspiration (Mahmoodzadeh, Mukhopadhyaya, & Valeo, 2020). Energy simulations were carried out on different types of roofs such as 100% turfing, 100% shrubs, and 100% trees. The results were compared with the baseline case of the exposed roof with no vegetation. Amongst the three types of plants, the roof covered with shrubs showed the most significant amount of reduction in energy consumption of 29 MWh (15%). Further study showed that the 15% savings in energy were due to low R-value in the base case of the exposed roof with no vegetation. The equivalent R-values of the roof assembly of the base case and green roof installation were assumed as 0.416 m^2K/W and 2.216 m^2K/W which indicates the poor insulation levels of the base case. Whereas the Building and Construction Authority of Singapore mandates a minimum R-value of 0.833 m^2K/W for heavyweight and 2 m^2K/W for lightweight roof construction in conditioned buildings. (SINGAPORE, 1986)

2) Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate (Olivieri, Di Perna, D'Orazio, Olivieri, & Neila, 2013): This paper carried out an experimental study on an extensive green roof to evaluate the thermal performance of green roofs in a Mediterranean climate zone specifically in the summer and exhibited that the vegetation on the experimental roof helped in reducing thermal gain by 60%. This result was validated for a roof that was heavily insulated with an R-value of 4.166 m^2K/W. The results were in contradiction with most of the previous research findings (Niachou, 2001) (Castleton, 2010) which point out that high insulation values are disadvantageous for green roof performance in the cooling period as the insulation traps the heat inside by minimizing the outgoing heat flux. Whereas this study displayed opposing findings on an experimental roof with EPS (expanded polystyrene) insulation of 12cm thickness and thermal conductivity of 0.035W/m K. It demonstrated that the roof covered with dense vegetation discharges more heat instead of absorbing it, and reduces the energy entering the internal environment by 60%. But it should be mentioned that a reduction in the incoming heat flux might not translate into the equivalent magnitude of reduction in energy consumption considering the heat transfer from other parts of the building envelope and via air infiltration. The high values of insulation will prevent the upward flow of heat gained by wall transmission, infiltration and internal heat gains, consequently entrapping it in the interior spaces thereby increasing the cooling load. The same has been validated by a study carried out by K. Lui and J. Minor which reports that the substantial values of insulation, though help in reducing heat flux, do not proportionally help in reducing the internal air temperature (Liu, 2005).

3) Dynamic U-value estimation and energy simulation for green roofs (Kotsiris, Androutsopoulos, Polychroni, & Nektarios, 2012): The paper aimed to determine the thermal transmittance coefficient (U-value) of green roofs under dynamic and real-scale conditions to account for internal biological processes occurring in the underlying layers due to the air circulation, moisture content and root system and its subsequent effect on evapotranspiration which is a key mechanism for a green roof's performance. This was done by estimating U-values of different combinations of substrate compositions and quantifying the energy savings for each composition. Five different green roof assemblies were constructed with variation in substrate components and depths. The U-values estimated via a dynamic approach gave lower values in comparison to the theoretically determined values. The results showed that despite the low dynamic U-values of the base roof, green roofs contributed to savings of cooling energy ranging from 11.8-15.45% in comparison to a conventional well-insulated roof. On the other hand, the heating loads were reduced marginally with some cases of load surges ranging from 4%-20%. It can be pointed out that the experiment for dynamic U-value estimation was performed under controlled thermal conditions with the ideal effectiveness of the insulation which might not represent the actual scenario. Additionally, this study presents quite opposite results for heating and cooling on a well-insulated roof and attributes the evapotranspiration process as the reasoning for high cooling load reduction even for highly insulated base roof which is contradictory with the previous major studies which state that high insulation values will hamper the process of evapotranspiration and will lead to increased cooling energy consumption (Mahmoodzadeh, Mukhopadhyaya, & Valeo, 2020) (Niachou, 2001).

4) A multi-criteria methodology for comparing the energy and environmental behavior of cool, green, and traditional roofs (Gagliano, Detommaso, Nocera, & Evola, 2015): This study represents a comparative analysis of the energy performance of three roof typologies i.e. a standard roof, a cool roof and a green roof in Mediterranean climate through a series of dynamic energy simulations using EnergyPlus. These roofs were subjected to a variable parameter of insulation thickness and thus ten different roof configurations were formed for investigation. The standard roof of the reference building was assumed as a 25 cm thick RC slab with no insulation. (U-value- 2.6 W/m^2 K). Results were collected for three scenarios of green roofs and cool roofs each, with a stepwise increase in the insulation thickness and thus the R-value of the assembly. These results, when compared with the baseline of the standard roof with no insulation, showed a range of 16-37% of savings in heating and approximately 85 % savings in cooling, which might be perceived positively. But when compared with a well-insulated roof (R-Value: 5.0 m^{2}K/W), these figures drop down to negative values for heating and 4-5% for cooling. With such low energy savings and high installation and maintenance costs, the energy-saving potential of green roofs does not seem conducive enough for their deployment for energy savings alone.

5) Investigating and analyzing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece (Santamouris, et al., 2007): This paper used a simulation approach using TRNSYS to investigate the thermal efficiency of a green roof system installed in a school building in Athens. A series of simulations were performed for two cases of a reference building: insulated and non-insulated. Scarce information has been given relating to the thermal

properties of the insulation used for simulation purposes, which makes it difficult to assess the range of benefits of a green roof system. The results claim strong figures of cooling load reduction for non-insulated (15-49%) and insulated (6-33%) buildings. Though the study does not find significant reductions in heating loads for both cases, it still regards the results as encouraging since it assumes that any attempt at reducing the cooling load hampers the heating load variation by increasing it. In fact, the insulated case shows contrasting results with an increase in the heating load if a green roof is installed on an insulated building. Whereas previous studies present opposing results for the heating season (Niachou, 2001) (Castleton H. F., 2010). Apart from this, if we look at the absolute values of energy for both the before and after green roof installation on an insulated roof, the percentage figures appear exaggerated, as the absolute value of energy savings lies between 0.4-0.8 kWh/m^2.

A review of the above research papers provides a deep understanding of the factors that have been missed out in concluding the results about the thermal efficiency of green roofs. The observations and comments made above were substantiated by the simulation study on the commercial benchmark buildings developed by the U.S. Department of Energy, the methodology of which has been presented in the following section.

CHAPTER 3. METHODOLOGY

This chapter describes the research methodology undertaken in this study. The energy simulations of green roofs have been carried out in combination with the optimization process. The results of the iterations from the optimization process were then analyzed using statistics software to conduct sensitivity analysis. The sensitivity analysis helped in examining the impact of various design parameters on the thermal performance of green roofs. The energy-saving figures obtained from the optimization process represented the maximum extent of the energy savings that could have been achieved under a particular set of constraints and settings. The energy savings benefit along with the other reviewed benefits of green roofs were converted into a monetary value to perform a cost-benefit analysis to study the economic viability of green roofs. This chapter, therefore, has been divided into sub-sections that describe the reference model for simulation and three sub-processes of optimization, sensitivity analysis, and cost-benefit analysis.

3.1 Experiment Goals and Objectives

To verify the results of previously carried out studies, this study aims to perform a series of simulations on a reference office building. It will also present near-optimal green roof parameters for different climate zones for well-insulated base roof assemblies. The findings of this study will be able to fulfill the following objective questions:

- Are green roofs a suitable design solution for reducing energy consumption in buildings with high roof insulation values?

- How does a green roof's performance vary with different climates and its component layer parameters?
- Which factors contribute the most to affecting the thermal performance of green roofs, apart from the insulation?
- Do the numerous benefits of green roofs recover the initial investment costs over its life cycle?
- Which benefit of green roof reaps the highest economic value based on the specific region taken in the study?

Figure 3 represents the experiment workflow which is arranged as follows:

1) The initial simulations were carried out to compare the energy consumption for two scenarios i.e. a conventional roof and a green roof. The simulations were performed in EnergyPlus, which is a building energy simulation engine. The Energy Use Intensities (EUI) of both scenarios will brief us about the performance of the green roof in a particular climate zone.
2) If the green roof performed for that climate zone, the optimization process was conducted to achieve minimum thermal loads by varying the selected parameters.
3) Based on the specified constraints on the design variables, the optimization process generated results for the various combinations of variable values.
4) The iteration results for each combination were compiled and used as an input for sensitivity analysis to be carried out in a statistical analysis tool-JMP.
5) The maximized energy savings were converted into capital values along with other benefits of the green roof to estimate the net present value of green roofs.

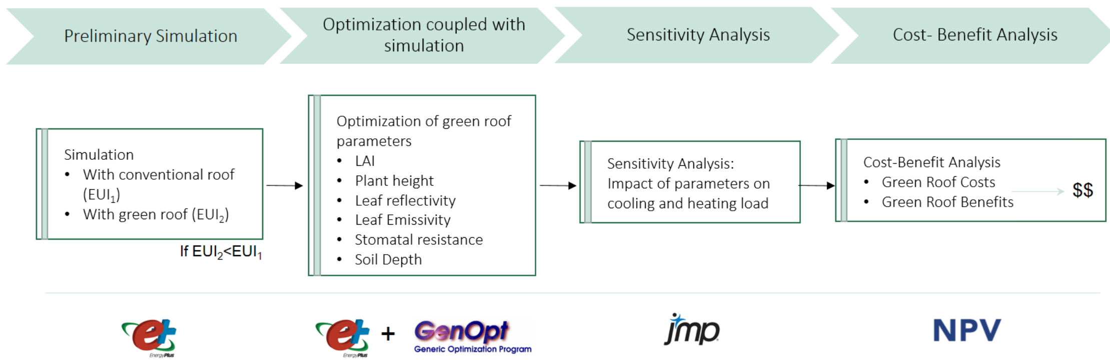


Figure 3 - Experiment workflow

3.2 Simulation Model

Green roofs were modeled on the reference medium and small-sized office buildings developed by the US Department of Energy. These reference building models cover 16 building typologies and 16 U.S. locations. The EnergyPlus input files of these models were available on the website of Office of Energy Efficiency and Renewable Energy which is a subsidiary unit of the U.S. Department of Energy. They provide a common benchmark for commercial building researches and help in providing consistency throughout different modeling approaches (Deru, et al., 2011). The objective of taking different heighted buildings was to study the impact of the roof-envelope ratio. It has been suggested by most of the previous studies that green roof implementation in a multistorey building helps in reducing the thermal load only for the uppermost floor which is present underneath the green roof. For a constant roof-envelope ratio, single-storey buildings show a higher percentage of energy savings compared to two or three storey structures (Martens, Bass, & Alcazar, 2008). These reference buildings were modeled for new construction and complied with ANSI/ASHRAE/IESNA Standard 90.1-2004. The medium size building had three floors with a gross floor area of 53,628 sq.ft. On the other hand, the small-sized office buildings were single-storied with a total floor area of 5500 sq.ft. The study was carried out for four climate zones. Arid (Phoenix), Mediterranean (Los Angeles), Tropical (Atlanta), Temperate (Chicago). The four climate zones had four different energy models in EnergyPlus with the same geometry but different system sizing. The three-storeyed building was divided into 18 zones which were all conditioned except the three plenum zones on the top of each floor. The exterior walls were made from a steel frame. The construction typology of the roof was IEAD (Insulation Entirely above Deck) with different R-values based on the climate zone. Cooling was electricity-based and heating was both electricity and gas-based in certain climate zones that were heating-dominated. Gas was also used for water heating systems. The single floor office building was divided into 5 conditioned zones and a non-conditioned attic zone. The walls used a thermal mass material for construction and the roof was sloped attic. The small-sized building used electricity for cooling and natural gas for heating. Energy use intensity values of the base case for both single and triple storeyed buildings have been presented in Figure 4 and Figure 5 with all end-use energies listed. Figure 6 represents the gas usage for four climate zones. It can be observed that gas is majorly used for heating in Atlanta and Chicago, whereas Los Angeles and Phoenix rely only on electrical heating as they are cooling dominated climates.

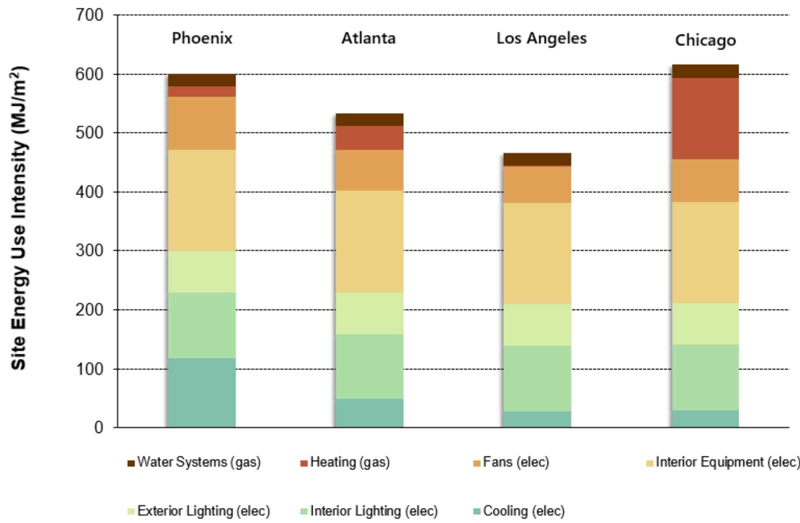


Figure 4 - Energy Use Intensity of reference small office building (Office of Energy Efficiency & Renewable Energy, 2011)

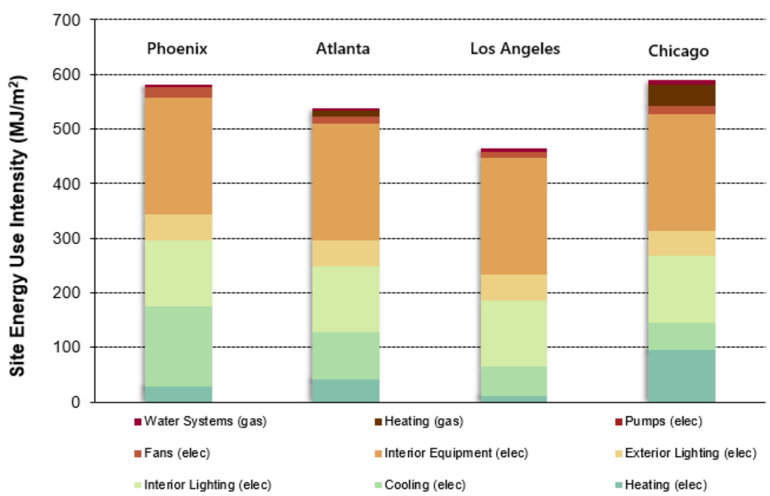


Figure 5 - Energy Use Intensity of medium office building (Office of Energy Efficiency & Renewable Energy, 2011)

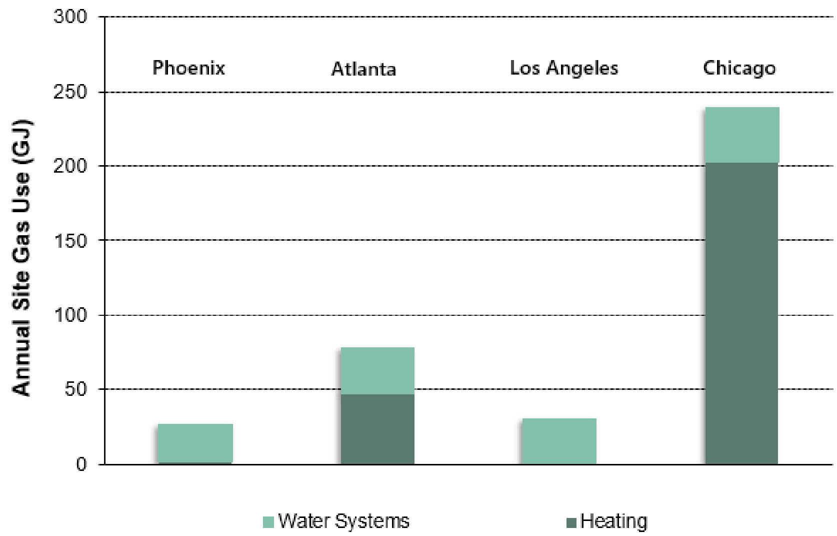


Figure 6 - Gas usage for different climate zones in medium office reference buildings (Office of Energy Efficiency & Renewable Energy, 2011)

Table 1 - EnergyPlus simulation settings for medium office reference building (Office of Energy Efficiency & Renewable Energy, 2011)

Building Design	Medium Office Reference Building (New Construction 90.1-2004)
Gross Floor Area	4982m^2
Floor Height	12m
Window Wall Ratio	0.33
Available Full Type	Electricity, Gas
Occupant Density	18.58 m^2/person
Lighting Load	10.76 W/m^2
Equipment Load	10.76 W/m^2
Ventilation rate	10L/s/person

HVAC System Details	System Type: MZ-VAV Heating Type: Gas Furnace and Electric Reheat Cooling Type: Precision air conditioning unit Fan Control: Variable
Exterior Walls	Construction Type: Steel Frame R-Value: 1.42 m^2K/W
Roof	Construction Type: IEAD R-value: 2.79 m^2K/W
Window	U-Factor: 2.62-5.84 W/m^2K SHGC: 0.25-0.39 Visible Transmittance: 0.11-0.41
Heating Set Point Temperature	21ºC
Heating Set Back Temperature	16ºC
Cooling Set Point Temperature	24ºC
Cooling Set Back Temperature	28ºC

Table 2 - EnergyPlus simulation settings for small office reference building (Office of Energy Efficiency & Renewable Energy, 2011)

Building Design	Small Office Reference Building (New Construction 90.1-2004)
Gross Floor Area	511m^2
Floor Height	3.1m
Window Wall Ratio	0.212
Available Full Type	Electricity, Gas
Occupant Density	18.58 m^2/person
Lighting Load	10.76 W/m^2
Equipment Load	10.76 W/m^2
Ventilation rate	10L/s/person
HVAC System Details	System Type: PSZ-AC Heating Type: Gas Furnace Cooling Type: Unitary DX Fan Control: Constant Volume
Exterior Walls	Construction Type: Thermal Mass R-Value: 0.42 m^{2}K/W
Roof	Construction Type: Attic R-value: 2.79 m^{2}K/W
Window	U-Factor: 2.62-5.84 W/m^{2}K SHGC: 0.25-0.39 Visible Transmittance: 0.11-0.41
Heating Set Point Temperature	21ºC
Heating Set Back Temperature	16ºC

Cooling Set Point Temperature	24ºC
Cooling Set Back Temperature	28ºC

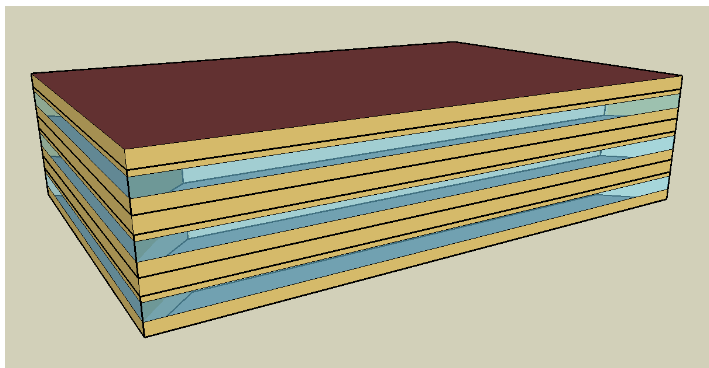


Figure 7 - 3D View of reference medium-sized office building (Office of Energy Efficiency & Renewable Energy, 2011)

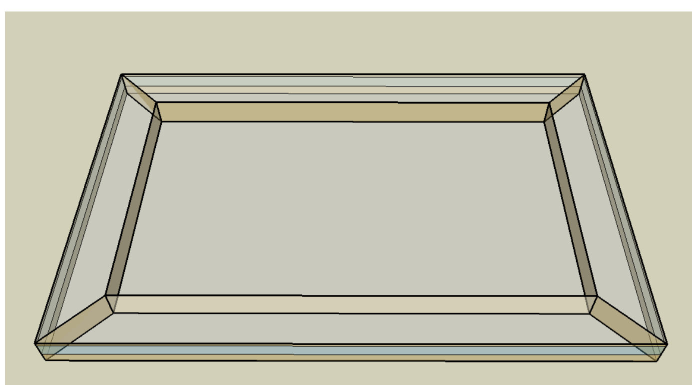


Figure 8 - Division of perimeter and core zones per floor level in reference medium-sized office building (Office of Energy Efficiency & Renewable Energy, 2011)

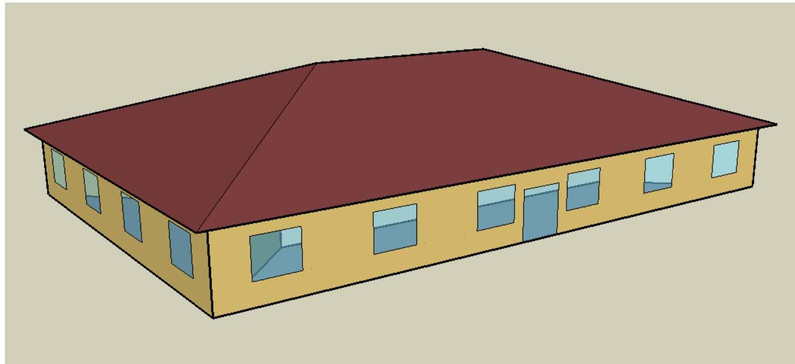


Figure 9 - 3D View of reference small-sized office building (Office of Energy Efficiency & Renewable Energy, 2011)

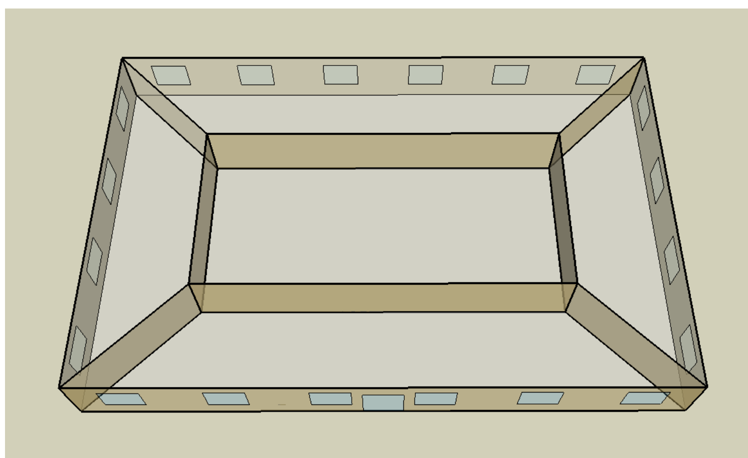


Figure 10 - Division of perimeter and core zones for ground floor level in reference small sized office building (Office of Energy Efficiency & Renewable Energy, 2011)

3.3 Optimization Methodology

Optimization in this study was carried out for a single objective function i.e. energy consumption of the building installed with a green roof. This study used GenOpt, a generic optimization program developed by Lawrence Berkeley National Laboratory. It helps in minimizing a cost function and can be coupled with other external simulation programs such as EnergyPlus, TRNSYS, DOE-2, SPARK, BLAST, etc. (Lara, et al., 2011). GenOpt has been mainly designed for optimization problems of the energy performance in buildings, and since EnergyPlus could read the input from text files and write the output in text files itself, it was convenient to run it with EnergyPlus without making any major internal modifications to either of the programs. Also, it allows the flexibility to choose an optimization algorithm from the available options in its library and implement a custom algorithm thus offering valuable assistance. GenOpt is capable of solving only single objective functions (Wetter M. , 2016).

Initialization of GenOpt required the following steps:

a) Specification of the design variables, either continuous or discrete, with constraints applied.

b) Stating the optimization algorithm to be used and input the corresponding settings

c) Formulation of the objective function by specifying the delimiters from the EnergyPlus output file.

d) Specifying the location of input and output files (Wetter M. , 2016).

GenOpt exchanges the information with EnergyPlus or any other coupled program using text-based files. It reads the input files, calls the simulation program, saves the results, and writes the output again in a text file. The input file can be modified using a predefined syntax. The variables in the objective function are evaluated by the simulation program and their value is written in a text-based output file of the program which is read by GenOpt. It calculates the objective function value and further writes it in a text file. Any possible errors, terminate the iteration cycle and are written in the GenOpt log file. If no errors are produced, the next iteration is carried out with the next set of input design parameters which are produced by the selected optimization search algorithm. The cycle keeps on iterating until an optimum solution is found or the stopping criteria such as maximum iteration is reached (Wetter M. , Design optimization with GenOpt. Building, 2000) (Wetter M. , 2016).

Initialization of GenOpt requires various input files (Wetter M. , 2016):

- The Command file contains all the independent design parameters with their constraints specified. A suitable optimization algorithm is also mentioned in the command file. (Figure 26) (Figure 27)
- The simulation input template file has the values of independent design parameters replaced by the corresponding variable names. The input values of these variables are filled by GenOpt in each iteration based on the selected optimization algorithm, which then further writes the simulation input file (Figure 25).
- An initialization file specifies the location of all the files. (Figure 28)
- The configuration file contains information on how to call the simulation program.

3.3.1 Justification for Optimization Algorithm

To solve the optimization problem proposed for the current study, various algorithms were analyzed and compared to each other to make an appropriate selection for efficient results. Though coordinate search could have been attractive because of its simplistic nature but its application was ruled out because it does not support global search and in some special cases of non-smooth multivariable function, it could get stuck and fail to achieve even a local minima. The Hookes-Jeeve algorithm posed a similar issue of not exploring the global structure of the objective function and is more susceptible to convergence to a local minimum. Also, this algorithm does not apply to discrete variables. Particle Swarm optimization algorithm can be applied to both continuous and discrete variables. It has a faster convergence rate, easily executable, and provides the possibility of convergence to global minima. A few earlier researches have been carried out by (Lu, Tang, Ji, & Tu, 2017) and (Wetter & Wright, A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization, 2004) to compare the performance of these optimization algorithms. Both of these studies were based on single-objective optimization and specified a cost function similar to the one proposed in the current study. The results of the study carried out by Wetter & Wright showed that the best optimization results were achieved by the hybrid algorithm of particle swarm and Hooke Jeeves, though it used a relatively larger number of simulations than GAs which gave not accurate but a closer solution in less number of simulations. Also, the study mentioned that stochastic algorithms such as particle swarm and GAs may often fail to get the desired results due to less number of simulations. Therefore, it depends on what the individual researcher is willing to trade off between accuracy and computational time. The study by Lu et al also recommended using a hybrid Generalized Pattern Search (GPS) algorithm with the Particle Swarm Optimization (PSO) algorithm in order to obtain global minima for a combination of discrete and continuous variables. This study, therefore, used the hybrid algorithm which made use of the characteristic of the global search of the PSO algorithm which was then refined by the Hookes Jeeve algorithm to improve upon the solution locally.

3.3.2 Optimization Settings

The objective of this optimization is to obtain a set of green roof parameters that help in achieving minimum energy consumption in comparison to the base case of the conventional roof when no green roof is installed, by keeping the prescribed insulation values of the roof intact, so as to observe the maximum extent of energy savings achieved for high roof insulation values with optimal design parameters. Since the thermal performance of a green roof is being evaluated, we will optimize annual energy consumption for heating and cooling of the reference building taken in the simulation model. The simulation settings for the base case of the conventional roof have been specified in Table 1. The design case incorporated a green roof layer over the original built-up flat (Insulation Entirely Above Deck) IEAD roof layer. The independent design parameters of the green roof, used in this optimization study are mentioned in Table 3. The initial values of these parameters were taken from the results of the preliminary study, which was based on a brute force approach. The cost function for annual thermal energy consumption for climate zones where only electricity was used for heating and cooling (Phoenix and Los Angeles) was formulated as follows:

$$\mathrm{Etot(x)} = \frac{\mathrm{Qheat(x)}}{\eta\mathrm{heat}} + \frac{\mathrm{Qcool(x)}}{\eta\mathrm{cool}}$$

where, Etot(x): annual thermal load

Qheat(x): annual heating load

Qcool(x): annual heating load

η: plant efficiencies for heating and cooling generation

Table 3: Optimization Design Parameters

Design Variables	Minimum	Maximum	Type
Plant Height	0.01	0.5	Continuous
Leaf Area Index	1	5	Discrete
Leaf Reflectivity	0.1	0.4	Continuous
Leaf Emissivity	0.8	1	Continuous
Minimum Stomatal Resistance	50	300	Discrete
Soil Depth	0.1	0.3	Continuous

For climate zones of Chicago and Atlanta, which required a reasonable amount of heating with gas as an additional fuel, the cost function was modified to incorporate the heating component from gas as follows:

$$\mathrm{Etot(x)} = \frac{\mathrm{Qheat(x)}}{\eta \mathrm{heat}} + \frac{\mathrm{Qcool(x)}}{\eta \mathrm{cool}} + \frac{\mathrm{Qgas(x)}}{\eta \mathrm{gas}}$$

where, Etot(x): annual thermal load

Qheat(x): annual heating load(electricity)

Qcool(x): annual heating load

Q(gasx): annual heating load(gas)

η: plant efficiencies for heating and cooling generation

3.4 Sensitivity Analysis

This research also aims to carry out a sensitivity analysis to study the extent of the impact of various design variables used in the optimization process, on the thermal efficiency of a green roof. This study used a statistical analysis software, JMP, developed by the SAS Institute for conducting the sensitivity analysis. Standard Least Squares method in JMP was used to fit the model data. This technique for model fitting in JMP includes a wide range of models such as analysis of variance, analysis of covariance, regression, and other miscellaneous models to analyze the designed experiment (Standard Least Squares Report and Options, 2020). The effect summary reports were studied to assess various model parameters and the significance of their effect. P-values and log worth were the two statistical values that were used to plot and analyze the significance. A p-value lower than 0.01 implied that the source variable (LAI/Plant Height/Leaf reflectivity/Leaf Emissivity/Soil Depth/Stomatal resistance) has an impact on the model response variables (Es_Heat, Es_Cool). The log worth values adjust the p-values by scaling them for presenting the values in the graph. Log worth is estimated using -log10 (p-value). If the log worth value exceeds 2, it indicates that the model parameter is significant at 0.01 level (Standard Least Squares Report and Options, 2020).

3.5 Cost-benefit Analysis

Cost-benefit Analysis (CBA) is widely carried out to analyze the economic feasibility of a project. This analysis helps the decision-makers in making informed decisions regarding the implementation of a policy/project with respect to its investment costs and revenue generation over a time period (Hoogmartens, Van Passel, Van Acker, &

Dubois, 2014). This study involved the cost-benefit analysis of green roofs by considering its investment cost and several benefits it provides. To determine the associated costs and benefits of a green roof, previous research papers were reviewed. Certain assumptions were required to define the boundary conditions of the system. Benefits and costs were expressed in monetary values to estimate the net value of the project. A variety of methods exist for analyzing the economic feasibility of a project. These include Benefit-Cost Ratio, Internal Rate of Returns, Net Present Value (NPV), and the Payback Period. Net present value is a method of carrying out a cost-benefit analysis that considers the difference between the total benefits reduced by total costs, both discounted to the present value. NPV provides an economic estimate of the net benefits over the life cycle of the project (Pan American Health Organization, 2017). A higher NPV indicates more positive net benefits and thus the project is considered more lucrative and vice versa. A discount rate is applied to the cash flows which occur across the life span of the project to convert the future returns into the present value. The discount rate addresses the consideration of inflation and the lost return on investment in the NPV (Dixon, 2012) (Pan American Health Organization, 2017). The financial costs are seen only from the perspective of the investor/owner and overlook any externalities. A comprehensive analysis considers the additional costs of negative external impact factors and benefit-costs of positive impact factors. These factors could be environmental and/or social. An extensive CBA also includes the costs of the mitigation measures to reduce the impact of negative externalities (Dixon, 2012). The scope of this study is limited to the financial and social cost-benefit analysis. This CBA aims to achieve a realistic scenario to provide economic implications for the installation of green roofs. The estimation values and processes were derived from the regulations, quotes from the contractors, and previous literature (Shin & Kim, 2019) (Breuning, 2014) (Nurmi, Votsis, Perrels, & Lehvävirta, 2013) (Bianchini & Hewage, Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach., 2012) (Kantor, 2017) (Porsche & Köhler, 2003) (David Evans and Associates, Inc, 2008).

3.5.1 Evaluation Assumptions

A thorough literature review was carried out to identify the costs and benefits of green roofs. For illustrative purposes, the commercial medium-sized office building of Chicago, developed by the U.S. DOE was taken as a reference. Several articles and reports, specific to the city of Chicago were reviewed to gain insights into the relevant information for this analysis. Based on the contractor's specification sheets and government-provided regulation and incentive documents, various subheads of costs and benefits were quantified. When the relevant information was not available for some specific subheads, the qualitative information was taken from the previous studies. As the analysis was specifically done for the Chicago region, it is stated that the results might not apply to other buildings and geographical locations. The following assumptions were made in this study to facilitate the computation of cost-benefit analysis.

- A coverage of 75% of the green roof on the base assembly was assumed.
- Based on the US Federal government mandates, the discount rate for environmental-related analysis should lie in a range between 2-5%. A discount rate of 4% was assumed for this study based on the figures used in the previous studies (Jeff, 2018) (Lilauwala & Gubert, 2014).

- The US inflation rate for the analysis period was forecasted to average around 2.2% by various US Federal agencies (Lilauwala & Gubert, 2014) (U.S. Department of Agriculture, 2020).
- Considering the green roof as a long-term investment, the life cycle of the green roof assembly was assumed to be of 50 years.
- It is assumed that plants can take approximately three years to fully establish on the growing media to reap the benefits of green roofs.
- It has been assumed that the design of the green roof considered in this cost-benefit analysis fulfills all the requirements to qualify for the specified government-based incentives and grants.

In the subsequent sections, the cost and benefits of green roofs gathered from various authentically published sources have been described, with their values converted into the present year 2020 dollar amount.

3.5.2 Investment Costs of Green Roofs

The investment costs of green roofs include its installation cost and annual operation and maintenance cost.

3.5.2.1 Green Roof Installation Cost

The construction cost of green roofs varies with the location, type of vegetative layer, and depth of the growing media. The cost of a standard extensive green roof in Chicago is approximately $20 per sq. ft. This cost comprises all the aspects of green roof development ranging from waterproofing membrane to planting vegetative layer and the labor cost. The movement of materials on the roof, installation of layers is a time-consuming and labor-intensive process that constitutes a significant portion of the installation cost (Fixr, 2020) (Green roofs NYC, 2020).

3.5.2.2 Maintenance Cost

The average annual maintenance cost of an extensive green roof was assumed as \$2/sqft. The maintenance cost of green roofs includes periodic pruning and fertilization, pest control, and irrigation. Extensive green roofs require less irrigation since most of the plants in the extensive roof are drought tolerant. Also, the maintenance cost of green roofs decreases after the initial two years of installment. The maintenance cost was considered as \$0.75 after the first two years (Green roofs NYC, 2020).

3.5.3 Benefits of Green Roofs

This section covers a wide variety of public and private benefits of green roofs. Each benefit will be treated separately to evaluate their monetary value to see whether the long-term cost savings can offset the initial capital cost and annual maintenance costs. Some of the obtained results are based on city-specific environmental/infrastructural parameters and policies.

3.5.3.1 Government Incentives

3.5.3.1.1 Floor Area Bonus

A Floor Area ratio bonus(FAR) of up to 2 FAR is granted by Chicago's zoning code, for structures that have more than 50% of their net roof area or a continuous 2000 sq. ft. covered with a green roof, whichever is greater. This bonus acts as an economic incentive for the developers, as they can increase their property value by increasing their built-up area and at the same time the built environment gets enhanced by the more square footage of green roof area. The additional Floor-Area-Ratio (FAR) can be translated into the monetary benefit of dollars (Savarani, 2019) (Peck & Joslin, 2019) (Using Incentive Programs to Promote Stormwater BMPs, 2009). The zoning ordinance for the downtown development of Village of Downer's Grove mentions a maximum FAR of 2.5 for Downtown Edge District. The addition of a bonus FAR of 2, can increase the built-up area by 3985.6 sq.m., thus leading to increased revenue of USD 1.3 million.

3.5.3.1.2 Green Permit Program

This policy aids in expediting the permit process and provides a waiver in consultation review fee, related to the planning process for new construction. To avail of these benefits, the projects are required to meet the criteria of incorporation of green technologies such as green roofs and meet other sustainability guidelines. The benefit tier with moderate sustainability requirements along with the green roof offers to waive the consultation code fee up to $25,000 (Kazmierczak & Carter, 2010) (Municipal Handbook, 2015).

3.5.3.1.3 Green Roof Improvement Program

This program applies to the commercial buildings in the financial district and awards grants up to $100,000 or 50% of the cost, if the structures have more than 50% of the net roof area vegetated with native species and the green roof should provide a significant view to the surrounding buildings (Kazmierczak & Carter, 2010) (Municipal Handbook, 2015).

3.5.3.2 Stormwater Management

Stormwater runoff is one of the major public issues due to impervious areas in dense urban settings. Vegetative media of green roofs helps in retaining and delaying the flow of stormwater which reduces the pressure on drainage systems of buildings. This has further allowed the developers to reduce urban stormwater infrastructure. Only eight of the municipalities of Chicago have imposed stormwater utility fees. The rest have implemented a flat fee system with monthly charges. A majority of utility fees are based on the area of the impervious surface. This fee covers the cost of the stormwater management plan and is based on Equivalent Runoff Units (ERUs). An ERU is approximately equal to 308 sq.m. and represents the average amount of impermeable area on a residential lot. The commercial properties are charged based on the number of ERUs. The present monthly rate in the municipalities such as Highland Park, Rolling Meadows, and Downers Grove ranges between $4-$8.4 per ERU. The average rate was assumed as $6/ERU. Since green roofs reduce the effective impervious area on the roof, based on the percentage area covered, they qualify for a significant discount (Stormwater Management

Strategy Paper , 2008) (The value of Stormwater Utilities for Local Governments in the Chicago Region, 2013).

3.5.3.3 Energy Savings

The thermal performance of vegetated roofs has been evaluated in the current study along with the optimization of design parameters. For Chicago, the energy savings figures were insignificant on a well-insulated roof. Since both electricity and gas were used for cooling and heating for the continental climate of Chicago, the fuel rates based on the current trends were assumed as 7¢/kWh for electricity and $1.24/therm (Chicago, IL Electricity Statistics, 2020).

3.5.3.4 Roof Longevity

The life span of green roofs is approximately two times greater than the conventional roofs. The life of the green roofs in this study has been assumed as 50 years, whereas a bitumen roof can only last for 20 years. Therefore the owner will have to pay the cost of reroofing every 20 years. The typical cost of the replacement for a built-up bituminous flat roof is $3.5- $6.5/sqft. This analysis considered $5/sqft. as the replacement cost for the conventional roof assembly (Gardei, 2016) (Bitumen Roof – Advantages and Disadvantages, 2020).

3.5.3.5 Carbon Sequestration

Green roofs are capable of reducing the level of carbon dioxide in the air by storing carbon in their leaves, soil, and other tissues. CO_2 is reduced by the vegetative layer of the green roof through the process of photosynthesis. This direct process of carbon sequestration is impacted by the properties of the vegetative layer and growing substrate. An extensive green roof consisting of Sedum as its top layer has the total carbon sequestration potential (above and below ground) of 4.67 kg C/sqm. This amount increases with the deeper substrates and implementation of other varieties of plants. (Whittinghill, Rowe, Schutzki, & Cregg, 2014) (Shafique, Xue, & Luo, 2020). Over the past few years, many lawmakers and climate groups have advocated the enaction of a carbon tax, but the challenge is that it has not been accomplished yet, but a few regions have imposed a fee on carbon emission to reduce the amount of carbon in the atmosphere. Presently no US state has a carbon tax, but at the time of writing this paper, Washington State lies in the prominence of being the first state to have its carbon tax initiative, I-1631 that proposes a carbon tax of \$15/ton of CO_2 and would rise at an annual rate of \$2/ton thereafter (Washington state (Initiative 1631), 2018).

3.5.3.6 Improvement in Air Quality

Urban city centers significantly contribute to the emissions of greenhouse gases and other pollutants that are harmful to human health and have adverse impacts on the global climate system. The vegetative layer of green roofs helps in reducing the concentration of air pollutants through the process of dry deposition. These pollutants include particulate matter (PM) and gaseous contaminants such as Nitrogen oxides (NO_x), Sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O3) (AECOM, 2017). A previously carried out study shows the annual removal rate of the various air pollutants by the extensive green roof is as follows: SO_2- 0.65g /m^2, NO_2-2.33 g /m2, PM_{10}- 1.12 g /m^2, O_3- 4.49 g /m^2 (Yang, Yu, & Gong, 2008). These results were specifically applicable to Chicago. Another research estimated the economic magnitude of the damages caused by the emission of these pollutants. The 14.8 million tons weight of SO_2 release, accounts for \$19.5 billion of damages. Though NO_2 and PM_{10} comprise half of the total tonnage of the emissions, they are responsible for only 20% of damages. The 21 million tons of NO_2 emissions cause damages worth \$6 billion. PM_{10} contributes 16 million tons of waste of total emissions and causes \$9.1 billion in damages. VOC's are responsible for the formation of ozone O_3 and other particulate matters. The VOC emissions of 17 million tons are responsible for \$12 billion worth of damages (Muller & Mendelsohn, 2007).

3.5.3.7 Increase in Property Value

The addition of sustainable amenities such as green roofs can potentially increase the marketability of a building and can often lead to an increase in rental rates thus adding to the revenue of the owner. Previous studies show that the incorporation of landscaping elements such as a green roof can add around 7% to the average rental rate of a medium-sized office property. Assuming the reference office to be in the Fulton Market, which is one of the prime urban locations of Chicago, it has a medium-range rental rate of \$31/sqft. Adding a 7% increase to it makes the rental rate around \$33.17/sqft (Clements, St Juliana, Davis, & Levine, 2013) (Chicago Office Space For Rent, 2020).

3.5.3.8 Reduction of the Urban Heat Island Effect

Urban Heat Islands (UHIs) are characterized by increased temperatures in dense urban settings in comparison to nearby exurban areas. The UHI could have a critical impact on the energy consumption of buildings. Green roofs have a higher albedo and through the process of evapotranspiration can help in the reduction of temperature in urban areas. A reduction in UHI can be estimated based on the difference between urban and rural temperatures (Ferguson, et al., 2008). A previous study carried out in the Chicago metropolitan area, simulated the summer period to assess UHI reductions under the impact of green roofs. This study developed a regional climate model at several spatial resolutions and the green roof fraction was increased by 25% in a series of simulations (Sharma, et al., 2016). The results were obtained for the innermost domain of 1km resolution. For 75% coverage of each roof with vegetation in a high-density commercial region, the daily average roof surface temperature was reduced by 6.27ºC which translated into energy savings of 268.56W/sqm/day (Razzaghmanesh, Beecham, & Salemi, 2016).

3.5.3.9 Reduction in noise pollution

Noise pollution from road traffic in urban areas could be a major issue. It can have the most severe health effects in the form of cardiovascular issues, lead to annoyance in people thus reducing their productivity, and can have a negative impact on the functioning of the ecosystems. Green roofs are considered effective measures to reduce sound transmission through the roof assembly (Magablih, 2019). The most effective green roof design can lead to a maximum reduction of 13dB (Galbrun & Scerri, 2017). The cost of noise pollution has been measured in multiple studies that have quantified the financial losses incurred due to reduced productivity and negative psychological effects and healthcare expenditures because of hearing disorder, hypertension, and coronary heart disease. A study that carried out an economic impact assessment of the environmental noise issue on 145.5 million of the US population suggests that a reduction of 5dB of noise level can reap annual economic benefits of $3.9 billion (Swinburn, Hammer, & Neitzel, 2015). Scaling the amount to fit the context of our study (population exposed to high decibel levels and decrease in relative risk with a reduction of 13dB), the green roofs can save up approximately $18,000 annually.

The results of the above-described experiments are presented in the subsequent sections. Optimization and sensitivity analysis have been carried out for the four climate zones whereas the results of the CBA are specific to the Chicago region. It needs to be underlined that the CBA in this study has considered only the direct costs and benefits of green roofs. Amongst all the benefits described above, the government incentives, energy savings, increase in the property value and saving of roof replacement cost will directly accrue to the building owner, whereas the rest of the benefits can be considered as public benefits. The other related externalities, both positive and negative have not been taken into account and will be considered in future studies. Also, the results of the CBA have been observed to majorly depend on the evaluation assumptions which might vary with the building typologies and federal policies of the considered region.

CHAPTER 4. RESULTS

This chapter presents the results of the optimization process, sensitivity analysis, and cost-benefit analysis. Optimization results have been presented for three storey office buildings and are compared with the results of single storey office buildings. The energy savings results of the optimization process were applied to the cost-benefit analysis which was specifically carried out for the city of Chicago. Table 4 below shows the heating and cooling degree days for the four climate zones considered in the study, which helped in comparing the heating and cooling requirements.

Table 4 - Heating and cooling degree days for four climate zones (BizEE Degree Days, 2020) (WolframAlpha, 2020)

Climate Zone	***Heating Degree Days***	***Cooling Degree Days***
Atlanta	2337	2645
Los Angeles	1620	650
Chicago	6004	1339
Phoenix	1100	5571

Atlanta experiences a humid subtropical climate, with hot & humid summer and cold winter. Table 4 shows that cooling loads dominate in Atlanta. It also receives abundant rainfall throughout the year. Los Angeles has a Mediterranean climate characterized by dry summers and mild winters. The precipitation is confined to the winter months. Chicago has a heating-dominated climate with cold and snowy winters. Summers are relatively cooler due to the presence of lake Michigan. Precipitation is moderate and evenly distributed. Phoenix has a desert type climate with dominating cooling loads. It experiences high temperatures in summers and mild warm winters. Precipitation is scarce and humidity levels are generally low.

4.1 Optimization Results

The optimization process in GenOpt was computationally expensive. For each climate zone, it ran for three days. Using the hybrid algorithm of Particle Swarm and Hookes-Jeeves, the results for each climate zone for medium-sized office buildings have been compiled in the subsequent figures. Figure 11 represents the percentage reduction in the total thermal load.

It can be observed from Figure 11 that Atlanta shows the highest percentage in energy reduction by the installation of the green roof, followed by Phoenix and Chicago. The Mediterranean climate of Los Angeles does not respond to green roof installation and shows minute increased energy consumption.

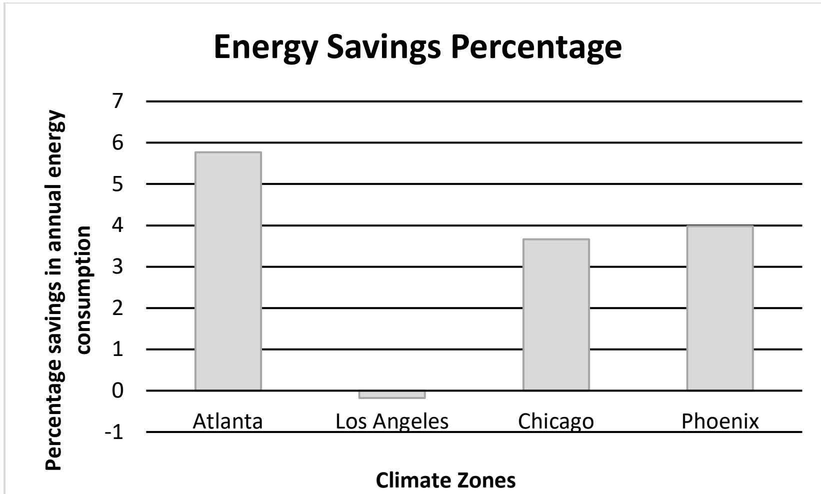


Figure 11 - Annual energy savings percentage in the medium-sized reference office building by green roof compared to base roof assembly with high insulation.

The simulation for Atlanta required 1890 simulations and converged after 36007 iterations. The reduction in total thermal load (Figure 12) was marginal with the absolute figure amounting to only 4 kWh/m^2. When we look at independent figures for heating and cooling (Figure 13 & Figure 14), it can be observed that the energy reduction figures are almost similar and both show the reduction trend which is why Atlanta leads in the energy savings percentage. The maximum value of LAI in the optimized parameters is one of the factors which leads to a reduction in cooling loads. On the other hand, low height plants and high insulation both contribute to a decrease in heating loads. Both plant height and LAI compete with each other to reduce the thermal load. However, the marginal reduction values can be attributed to the high R-value of the roof assembly. A well-insulated roof acts as a thermal barrier, thus suppressing the heat dissipation from the indoor space through the roof assembly. The optimized design parameters in Atlanta show a higher leaf area index, which means a high projected area of the leaves which shades the exposed soil surface area and maintains the difference between the outdoor air and the roof surface temperature. Soil depth was the major influencing factor on the heating load and in the optimized values, it reaches the maximum value provided in the constraints since it provides the thermal inertia thus resulting in lower heat flux and provides insulation effects.

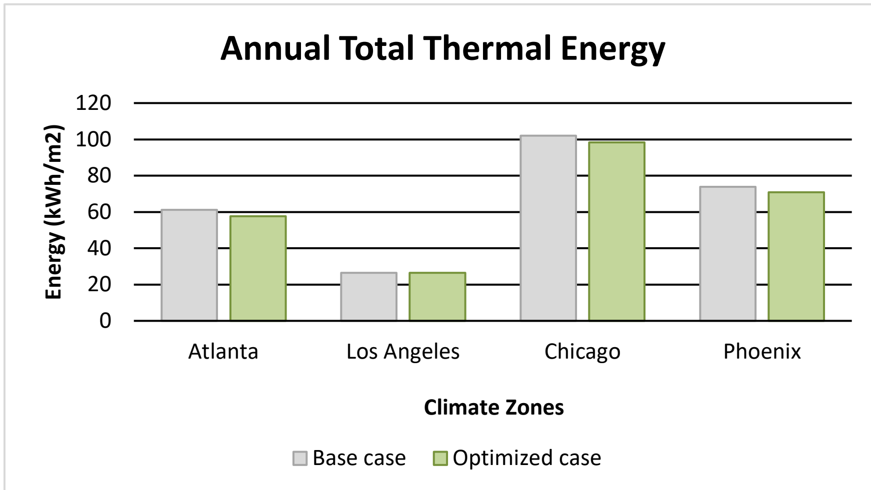


Figure 12 - Annual thermal load reduction in the medium-sized reference office building by the green roof compared to the base roof assembly with high insulation.

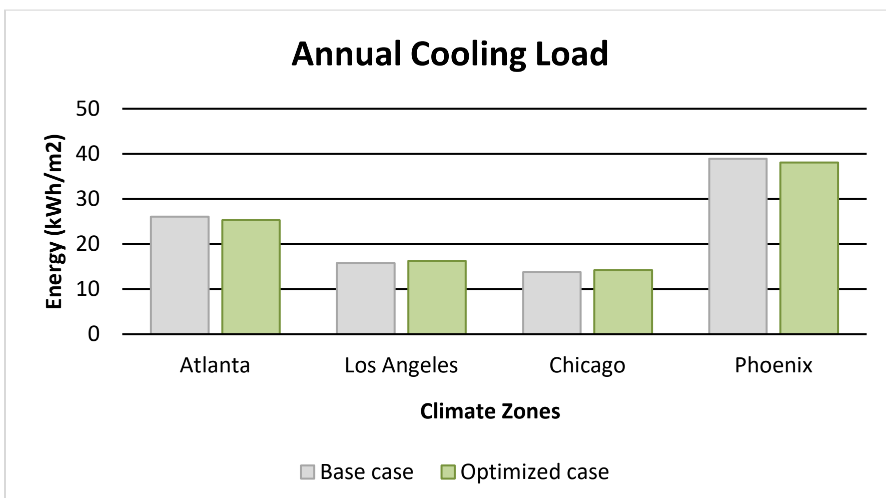


Figure 13 - Annual cooling load reduction in the medium-sized reference office building by the green roof compared to the base roof assembly with high insulation.

The optimization process for Los Angeles required 1064 simulations and 151 iterations to converge to the optimal solution. The Mediterranean climate showed negative energy savings, though, the increase in the total thermal load was insignificant (0.046 kWh/m^2). Heating and cooling results show opposite trends and the increase in the cooling load outweighed the decrease in the heating load. This result is justifiable because Los Angeles experiences mild winters with heating loads contributing only 14% to the total thermal load, which makes the scope of green roofs in reducing heating energy quite limited. LAI dominated the effects of plant heights. Though, both LAI and plant height reached their near favorable extremes, the required thermal gradient for evapotranspiration was suppressed by high insulation values which caused the cooling loads to increase.

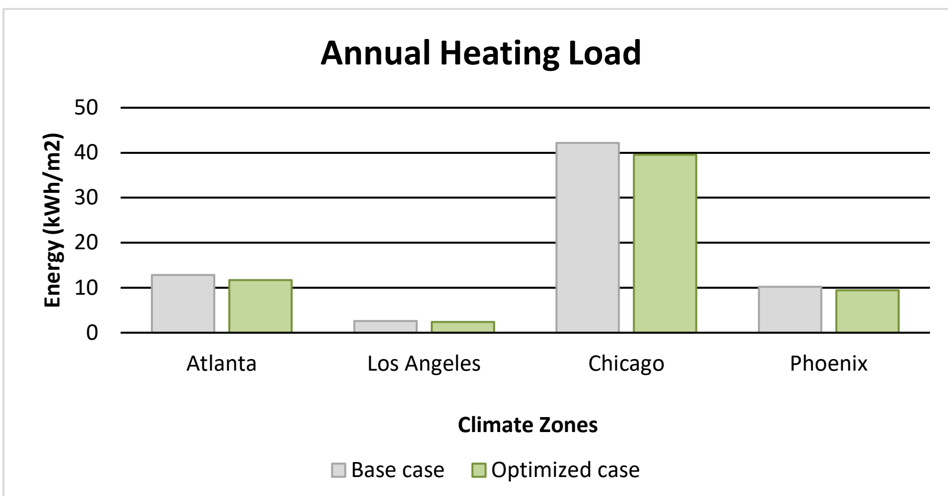


Figure 14 - Annual heating load reduction in the medium-sized reference office building by the green roof compared to the base roof assembly with high insulation.

Chicago shows a reduction of 3.6% in energy consumption. Though high insulation values helped in decreasing the heating loads fueled by both electricity and gas, the high R-value led to a change in the cooling loads by 0.5kWh/m^2. The net reduction, thus, with a cooling load increase comes out to be positive. This can be validated by the results obtained by the study carried out by La Roche and Berardi (La Roche & Berardi, 2014). The analysis for Chicago shows increased values of cooling load with the insulation values of 4 and 8 inches. The optimal parameters for Chicago show that both plant height and LAI are attaining less than average values to allow for solar radiation on the roof assembly for the reduction in heating load. Substrate depth was maximized in the optimal solution to improve upon the insulation properties of the roof. It is also to be noted that the climate zone of Chicago shows the maximum pullback in the heating load, out of all the four climate zones indicating the suitability of green roofs in heating-dominated climates for the high insulation setting taken in this study.

The annual thermal load of Phoenix was reduced by 3 kWh/m^2. Since Phoenix is a cooling dominated climate, with intense solar radiation and low humidity, the high evapotranspiration rate should have produced some notable savings in the cooling load. But the results shown in Figure 13 demonstrate contradictory results with no major change in energy savings. This can be again credited to the insulation thickness which supersedes the effect of achieved favorable values of stomatal resistance and LAI values; this reflects the significance of insulation values in determining the thermal efficiency of the green roofs. Whereas, a high soil depth and low plant height contribute to a minor decrease of 0.82 kWh/m^2 in the heating loads. The desert type of climate experiences sunny and warm winter afternoons which further keep the heating loads under control.

Table 5 Optimal Design parameters for four climate zones

Design Variables	*Atlanta*	*Los Angeles*	*Chicago*	*Phoenix*
Plant Height	0.05	0.5	0.1	0.1
Leaf Area Index	5	4	5	5
Leaf Reflectivity	0.1	0.1	0.1	0.15
Leaf Emissivity	0.8125	0.9	0.8	0.95
Minimum Stomatal resistance	170	220	80	50
Soil Depth	0.3	0.3	0.3	0.3

The simulations were carried out for small-sized reference office buildings as well with a single storey. This building didn't use electricity for heating, so the objective function for the optimization was formulated accordingly. The energy savings figure for single storey office buildings have been represented in Figure 15 and the results are compared to the energy savings figure of the triple storey office building.

It was observed that energy savings by green roofs get enhanced if the roof-envelope ratio is increased. In the case of a tall triple storey office building, the roof accounts for only 46% of the total building envelope, and this percentage increases by 22% for the single storey building. These results can be validated by previous researches as well, where (Suszanowicz & Kolasa Więcek, 2019) (Castleton, Stovin, Beck, & Davison, 2010) state that the floors directly under the green roof experience the highest energy savings amongst all floors. This is because a building with a low roof to wall ratio will experience heat flux through its larger envelope that would be hard to control by a green roof.

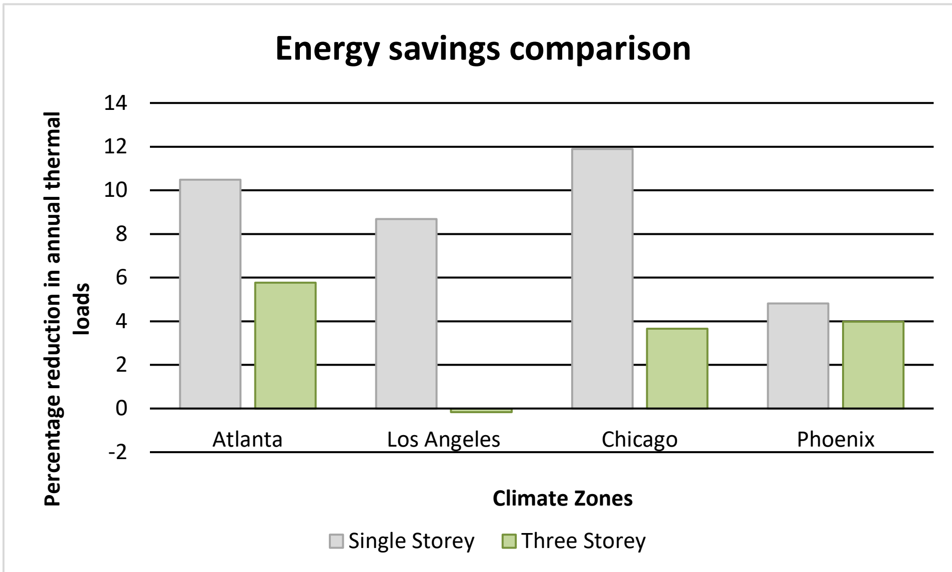


Figure 15 - Comparison of energy savings by the installation of the green roof for single storey & triple storey reference office building

A larger area of the roof will make sure that the heat is majorly dissipated through the roof, thus boosting the evapotranspiration process and reducing cooling loads. In the heating season, the majority of the heat loss is prevented by the extra insulation provided by the green roof. With less roof-envelope ratio, the heat retained by the green roof will be lost via the envelope.

4.2 Sensitivity Analysis Results

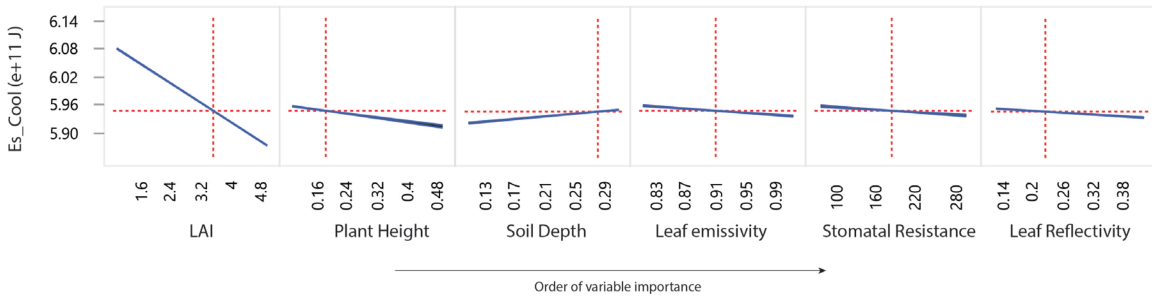
A sensitivity analysis was carried out using the iterations of optimization results to gain knowledge of the factors impacting the heating and cooling load for each climate zone. The results obtained from the sensitivity analysis helped in understanding the converged values of the optimization. The heating and cooling loads were converted into source energy consumptions (Es_Cool, Es_Heat) using plant efficiencies.

$$\mathrm{Es\_Cool} = \frac{\mathrm{Qcool(x)}}{\mathrm{\eta cool}}$$

$$\mathrm{Es\_Heat} = \frac{\mathrm{Qheat(x)}}{\mathrm{\eta heat}}$$

4.2.1 Atlanta

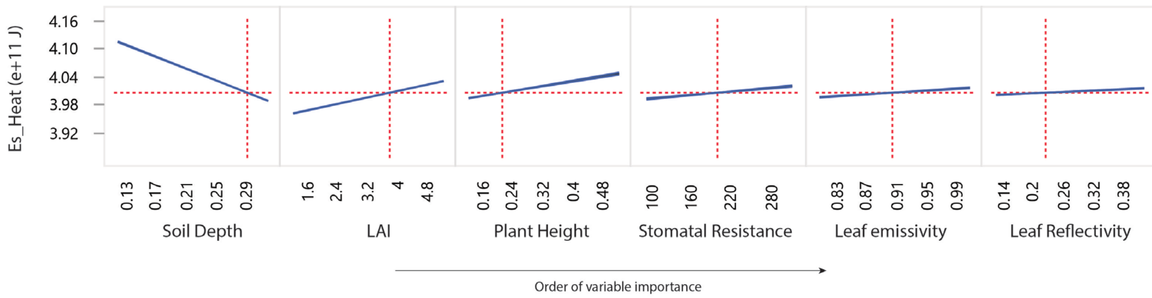
The results for Atlanta in Figure 16 indicate that all the design parameters are significant for the estimation of cooling loads (Es_Cool), since the log worth value of all the parameters exceeding 2. The cooling load shows its responsiveness to mainly the LAI. The cooling load decreases with the increase in the LAI and plant height and the effects of LAI supersede the effects of plant height in its importance. The LAI significantly affects the evapotranspiration rate of the green roof which helps in providing cooling effects. For various vegetation species, LAI might vary across the seasons. A higher LAI improves the heat flux of the vegetative layer, thereby reducing the temperature difference between the green layer and the ambient environment which helps in mitigating the urban heat island. Other parameters such as soil depth, leaf emissivity, stomatal resistance, and leaf reflectivity have a minor impact on the variation of cooling loads.



Source	LogWorth	PValue
LAI	12096.58	0.00000
Soil Depth	348.550	0.00000
Leaf Reflectivity	194.546	0.00000
Plant Height	110.699	0.00000
Leaf Emissivity	63.694	0.00000
Stomatal Resistance	21.631	0.00000

Figure 16 - Sensitivity analysis results for cooling loads of Atlanta a) Prediction Profiler showing the variation trend in Es_Cool with design parameters b) Effect summary showing the impact of design parameters on Es_Cool

Figure 17 shows that the heating load (Es_Heat) is mostly affected by the thickness of the soil substrate followed by the LAI value. The additional depth of the soil layer improves upon the existing insulation and helps in reducing the heat loss through the roof surface in the winter, thus stabilizing the internal temperature. On the other hand, the heating loads rise with the increase in the LAI since the plant canopy restricts the incoming solar radiation, and thus the corresponding flux through the soil layer decreases. Though the heating load is sensitive to the changes in other parameters as well such as plant height, stomatal resistance, leaf reflectivity, and emissivity, their decreasing order of importance has been presented in Figure 16.



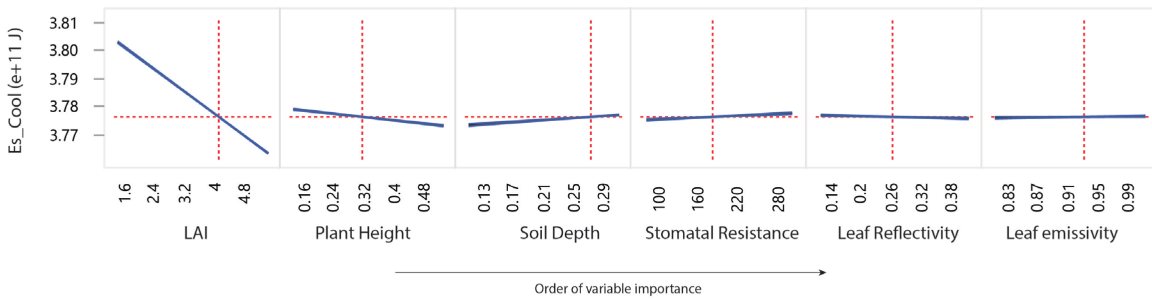
Source	LogWorth	PValue
Soil Depth	6736.215	0.00000
LAI	3789.469	0.00000
Plant Height	245.738	0.00000
Leaf Reflectivity	159.515	0.00000
Leaf Emissivity	77.914	0.00000
Stomatal Resistance	60.228	0.00000

Figure 17 - Sensitivity analysis results for heating loads of Atlanta a) Prediction Profiler showing the variation trend in Es_Heat with design parameters b) Effect summary showing the impact of design parameters on Es_Heat

4.2.2 Los Angeles

The sensitivity analysis results for the Mediterranean climate of Los Angeles is presented in Figure 18. It is observed that in the estimation of cooling loads, leaf emissivity does not play any role going by its PValue and LogWorth. Amongst the parameters which strongly affect the cooling load in Los Angeles, LAI comes out as the major factor. In an interactive relationship between LAI and plant heights, LAI is more effective in reducing the cooling loads (Mahmoodzadeh, Mukhopadhyaya, & Valeo, 2020). Soil Depth also plays a major role in influencing the cooling loads. It can be inferred from the fact that Los

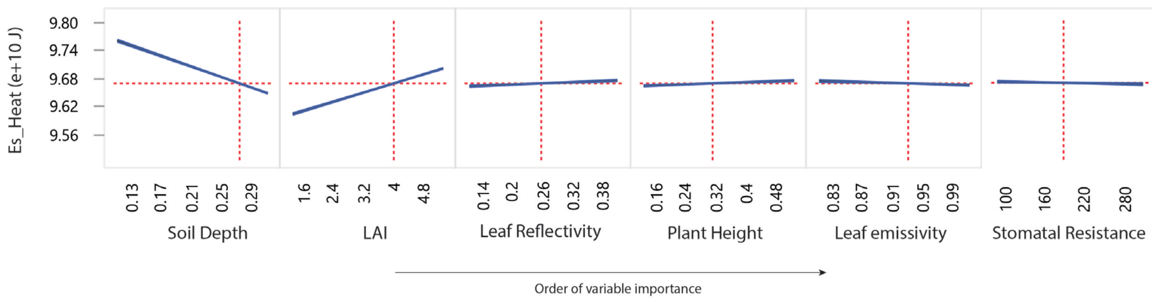
Angeles doesn’t experience extreme summers, thus soil depth is effective in reducing cooling loads, unlike other climate zones.



Source	LogWorth	PValue
LAI	3057.408	0.00000
Plant Height	123.566	0.00000
Soil Depth	46.476	0.00000
Stomatal Resistance	11.773	0.00000
Leaf Reflectivity	3.469	0.00034
Leaf Emissivity	1.148	0.07114

Figure 18 - Sensitivity analysis results for cooling loads of Los Angeles a) Prediction Profiler showing the variation trend in Es_Cool with design parameters b) Effect summary showing the impact of design parameters on Es_Cool

When it comes to the heating loads, soil depth is again playing a significant role because of the insulation properties it provides. Soil depth is followed by LAI; the heating loads are proportional to the LAI values since high LAI blocks the required solar radiation in the heating season. Other factors such as plant height, stomatal resistance, leaf reflectivity, and emissivity, though influence the heating load, have insignificant contributions. The order of importance of the independent variables is varying for cooling and heating loads. Stomatal resistance is coming high in the order of cooling loads as it affects the evapotranspiration rates in plants. On the other hand, it stands last in the order of heating loads.

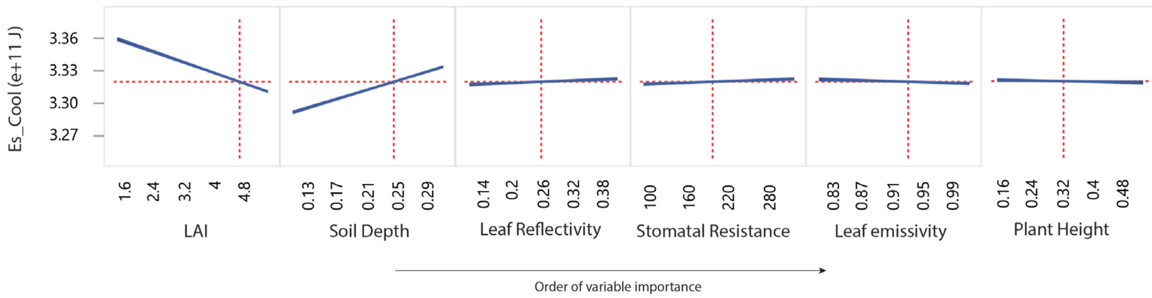


Source	LogWorth	PValue
Soil Depth	1055.936	0.00000
LAI	962.571	0.00000
Plant Height	14.310	0.00000
Leaf Reflectivity	11.691	0.00000
Leaf Emissivity	6.126	0.00000
Stomatal Resistance	2.323	0.00476

Figure 19 - Sensitivity analysis results for heating loads of Los Angeles a) Prediction Profiler showing the variation trend in Es_Heat with design parameters b) Effect summary showing the impact of design parameters on Es_Heat

4.2.3 Chicago

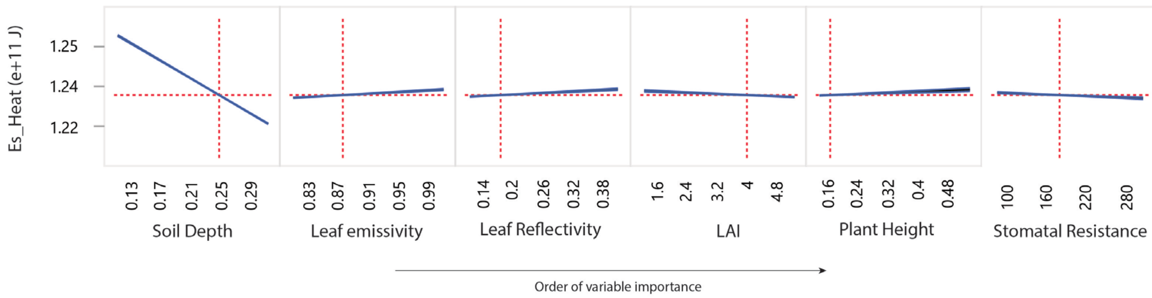
The results for the climate zone of Chicago in Figure 20 show that cooling loads are majorly influenced by LAI and Soil Depth. It can be observed here that plant height doesn't have any impact on the cooling loads of Chicago. That implies that an increase in the plant height doesn't always lead to a reduction in cooling loads and it mostly depends on its relationship with LAI and climate. Stomatal resistance and other leaf parameters again have a marginal impact on the cooling loads.



Source	LogWorth	PValue
LAI	1028.029	0.00000
Soil Depth	344.261	0.00000
Leaf Reflectivity	91.871	0.00000
Leaf Emissivity	32.071	0.00000
Stomatal Resistance	23.210	0.00000
Plant Height	0.029	0.93560

Figure 20 - Sensitivity analysis results for cooling loads of Chicago a) Prediction Profiler showing the variation trend in Es_Cool with design parameters b) Effect summary showing the impact of design parameters on Es_Cool

Heating loads of Chicago are affected by all the considered design parameters. Amongst all the design variables, soil depth has a key role to play in reducing the heating loads as it lowers the heat flux through the roof assembly. As Chicago is a heating-dominated climate, the effect of soil depth is more pronounced in this climate zone as compared to the others. A critical thing that can be noticed from Figure 21 is that leaf emissivity and leaf reflectivity are lying ahead in the order of importance and they both have a positive relationship with the heating loads. With a lower plant albedo, the latent heat flux crossing the vegetative layer is higher resulting in a higher foliage temperature which helps in reducing the heating load.

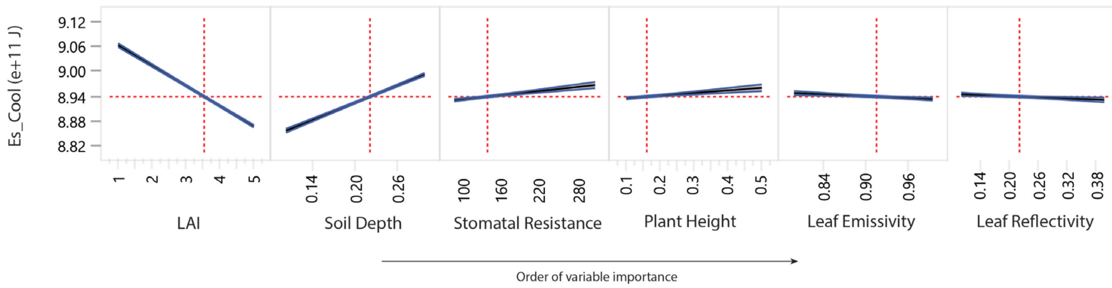


Source	LogWorth	PValue
Soil Depth	2923.932	0.00000
Leaf Emissivity	50.174	0.00000
Leaf Reflectivity	36.528	0.00000
LAI	24.040	0.00000
Stomatal Resistance	9.829	0.00000
Plant Height	9.810	0.00000

Figure 21 - Sensitivity analysis results for heating loads of Chicago a) Prediction Profiler showing the variation trend in Es_Heat with design parameters b) Effect summary showing the impact of design parameters on Es_Heat

4.2.4 Phoenix

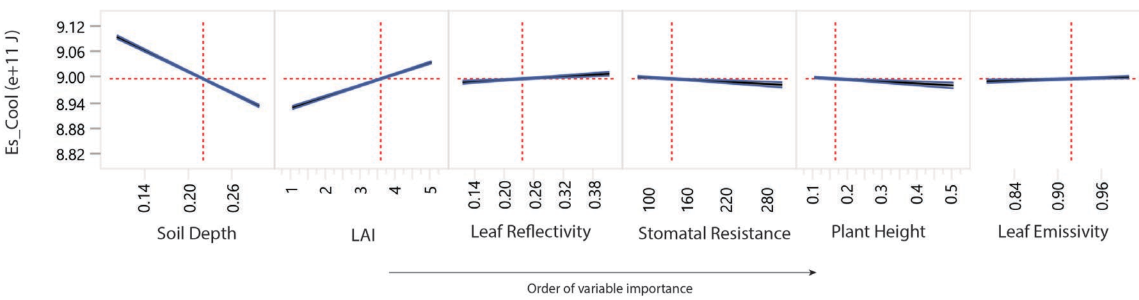
The results for the desert type climate of Phoenix are represented in Figure 22 and Figure 23. LAI and soil depth play a significant role in the estimation of cooling loads; where LAI shows an inverse relationship, on the other hand, soil depth has a positive impact. The cooling loads increase with the soil depth because the substrate layer provides an added insulation on top of the existing high insulation which doesn't allow the inside heat to escape.



Source	LogWorth	PValue
LAI	420.552	0.00000
Soil Depth	227.011	0.00000
Stomatal Resistance	13.204	0.00000
Plant Height	6.953	0.00000
Leaf Emissivity	3.772	0.00017
Leaf Reflectivity	2.530	0.00295

Figure 22 - Sensitivity analysis results for cooling loads of Phoenix a) Prediction Profiler showing the variation trend in Es_Cool with design parameters b) Effect summary showing the impact of design parameters on Es_Cool

Stomatal resistance overrides the effect of plant height since Phoenix is cooling dominated climate with extreme solar radiation and low humidity. This type of climate is effective for high evapotranspiration rates, which makes the role of stomatal resistance more impactful. Lower stomatal resistance will lead to increased evapotranspiration rates, thus reducing the cooling loads.



Source	LogWorth	PValue
Soil Depth	371.852	0.00000
LAI	236.246	0.00000
Leaf Reflectivity	6.882	0.00000
Plant Height	5.475	0.00000
Stomatal Resistance	5.291	0.00001
Leaf Emissivity	2.605	0.00248

Figure 23 - Sensitivity analysis results for heating loads of Phoenix a) Prediction Profiler showing the variation trend in Es_Heat with design parameters ad their order of significance b) Effect summary showing the impact of design parameters on Es_Heat

The heating loads of Phoenix are majorly impacted by the soil depth and LAI, though both show opposite trends. With an increase in the LAI, there is a proportionate increase in the heating loads since it exposes less soil to the solar radiation thus resulting in lower surface temperature. Leaf reflectivity and leaf emissivity show a similar shift as the thermal radiation absorption is reduced. Since the heating loads of Phoenix have a lower contribution of approximately 20% in the total thermal loads, the scope of parameters such as plant height and stomatal resistance is quite narrow.

4.3 Cost-Benefit Analysis

The Net Present Value (NPV) was used as an evaluation measure for the cost-benefit analysis of green roofs. The formula used for this measure is as follows (Dixon, 2012) :

$$\text{NPV} = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t}$$

Where, B: Total benefits in the t(th) year

C: Total costs in the t(th) year

r: Discount Rate

n: Age of green roof

The cash flows in this measure consist of the difference between the benefits and the costs discounted to the present value over the time in which they occur. If the NPV is positive, the project is considered economically feasible and it will provide more returns over the proposed time frame than its investment cost. The estimated values of the costs and benefits related to the green roofs have been summarized in Figure 24. No discount rate was applied to the costs invested in the initial year. Considering 75% application of green roof over the roof area, the net green roof coverage came out to be 1245.75 sqm. The construction cost, labor cost, and maintenance costs were considered in the initial year. The government provided incentives were the only benefits in the starting year. It was assumed that plants take a minimum of three years to fully establish on the green roof assembly. Therefore, the provision of benefits of green roofs was taken after the third year of its installation. The replacement cost of the conventional bitumen roof was taken every 20 years, so it appeared twice in the entire life cycle of the project. Also, the inflation rate of 2.2% was applied in each cost and benefit to capture the future trend of the price index.

The results of this cost-benefit analysis could be applied for the specific region of Chicago and were based on certain assumptions. These results will vary with the change in the climate zone, urban settings, economic scenario, and federal policies of the considered location.

The net aggregate of the discounted cash flows over the assumed life cycle of 50 years was calculated to estimate the NPV, which came out to be USD 190 million. This indicates that a green roof is not only just a feasible option but also a profitable strategy for increasing the resilience to climate change impacts. By observing the benefits sections in Figure 24, it can be stated that a major percentage of the initial investment cost of green roofs was recovered by the Green Roof Permit Program which provided the incentive of 50% cost compensation in addition to other incentives policies. The maintenance cost of green roofs was assumed as $2/sqft for the initial three years to help in its full development. After the vegetative layer gets matured, the maintenance cost is reduced to $0.75/sqft which is applied for the subsequent years. Similarly, the benefits of green roofs were applied after three years when it got fully developed. Amongst all the benefits of green roofs, reduction in the UHI provided maximum economic benefit, since it catered to a larger scale. The maximum revenue in the private benefits was provided by an increase in the rental rates of office spaces because of the pleasing aesthetic view that green roofs provide.

The recreational benefit of green roofs was not considered in this study, since the extensive typology was assumed, which does not allow any kind of access over it. This was followed by the sound attenuation benefit, which helped in saving almost a million-dollar over 50 years. Though the profit of not investing in the bituminous roof replacement occurs only twice in the life cycle of the project, it helped in saving a significant amount of money and time. Because of the uncertainties in the implementation of the federal policies regarding carbon and other poisonous gas emissions, the benefits of improvement in air quality and carbon sequestration were not fully realized and thus showcased limited savings. The most touted benefit of green roofs was the one that provided the least amount of savings, contributing only 4 million USD over the entire life cycle. When the annual discounted cash flows are observed over 50 years, it can be suggested that the benefits of the green roofs start reaping after the initial 3-4 years of rigorous maintenance. When we remove the externalities and other public benefits, the revenue generated by the installation of the green roof by the owner due to enhanced property values is sufficient enough to recover its high installation costs. Considering only the economic aspects, green roofs have an architectural advantage over other conventional roofs, since they are considered a landscaping element that could provide a passive recreation area and thus giving the space an economic edge by enhancing the salability of the buildings.

	Cost			Benefits													
Year	Construction cost	Labour Cost	Maintenance cost	Govt Incentives	Stormwater	Energy Savings	Roof Longevity	Carbon Sequestration	Improvement in air qualiy	Increase in property value	Reduction in UHI	Reduction in noise pollution	Discount Factor	Total benefits	Total Cost	B-C	Disc. Annual Cash Flows
0	268182.828	134091.414	0	125000	0	0	0	0	0	0	0	0	1	125000	402274.242	-277274.24	-277274.242
1			26818.2828										1.04	0	26818.2828	-26818.283	-25786.81038
2			27408.28502										1.0816	0	27408.28502	-27408.285	-25340.5002
3			28011.26729										1.124864	0	28011.26729	-28011.267	-24901.91462
4			10727.31312		288	4918.84		319.3891223	6.638034896	9699.278946	6861708	18677.1134	1.169859	6895617.26	10727.31312	6884889.95	5885232.781
5			10963.31401		294.336	5027.054		361.9743386	6.784071663	9912.663083	7012665.58	19088.0099	1.216653	7047356.398	10963.31401	7036393.08	5783402.209
6			11204.50692		300.811392	5137.65		404.5595549	6.93332124	10130.74167	7166944.22	19507.94611	1.265319	7202432.86	11204.50692	7191228.35	5683332.226
7			11451.00607		307.4292426	5250.678		447.1447712	7.085854307	10353.61799	7324616.99	19937.12093	1.315932	7360920.068	11451.00607	7349469.06	5584992.458
8			11702.9282		314.192686	5366.193		489.7299875	7.241743102	10581.39758	7485758.57	20375.73759	1.368569	7522893.058	11702.9282	7511190.13	5488353.056
9			11960.39262		321.1049251	5484.249		532.3152038	7.40106145	10814.18833	7650445.25	20824.00382	1.423312	7688428.516	11960.39262	7676468.12	5393384.68
10			12223.52126		328.1692334	5604.903		574.9004201	7.563884802	11052.10047	7818755.05	21282.1319	1.480244	7857604.818	12223.52126	7845381.3	5300058.495
11			12492.43873		335.3889565	5728.21		617.4856364	7.730290268	11295.24668	7990767.66	21750.3388	1.539454	8030502.061	12492.43873	8018009.62	5208346.16
12			12767.27238		342.7675136	5854.231		660.0708527	7.900356654	11543.74211	8166564.55	22228.84626	1.601032	8207202.107	12767.27238	8194434.83	5118219.821
13			13048.15237		350.3083989	5983.024		702.656069	8.0741645	11797.70444	8346228.97	22717.88087	1.665074	8387788.617	13048.15237	8374740.46	5029652.101
14			13335.21173		358.0151837	6114.651		745.2412853	8.251796119	12057.25393	8529846.01	23217.67425	1.731676	8572347.093	13335.21173	8559011.88	4942616.095
15			13628.58638		365.8915177	6249.173		787.8265016	8.433335634	12322.51352	8717502.62	23728.46309	1.800944	8760964.919	13628.58638	8747336.33	4857085.359
16			13928.41528		373.9411311	6386.655		830.4117179	8.618869017	12593.60882	8909287.68	24250.48927	1.872981	8953731.401	13928.41528	8939802.99	4773033.903
17			14234.84042		382.167836	6527.161		872.9969342	8.808484136	12870.66821	9105292	24784.00004	1.9479	9150737.808	14234.84042	9136502.97	4690436.184
18			14548.00691		390.5755284	6670.759		915.5821505	9.002270787	13153.82291	9305608.43	25329.24804	2.025817	9352077.419	14548.00691	9337529.41	4609267.098
19			14868.06306		399.16819	6817.515		958.1673668	9.200320744	13443.20702	9510331.81	25886.4915	2.106849	9557845.564	14868.06306	9542977.5	4529501.974
20			15195.16045		407.9498902	6967.501	103606.9504	1000.752583	9.402727801	13738.95757	9719559.11	26455.99431	2.191123	9871746.623	15195.16045	9856551.46	4498401.422
21			15529.45398		416.9247877	7120.786		1043.337799	9.609587812	14041.21464	9933389.41	27038.02618	2.278768	9983059.314	15529.45398	9967529.86	4374087.033
22			15871.10197		426.0971331	7277.443		1085.923016	9.820998744	14350.12136	10151924	27632.86276	2.369919	10202706.25	15871.10197	10186835.1	4298389.964
23			16220.26621		435.47127	7437.547		1128.508232	10.03706072	14665.82403	10375266.3	28240.78574	2.464716	10427184.48	16220.26621	10410964.2	4224002.338
24			16577.11207		445.0516379	7601.173		1171.093448	10.25787605	14988.47216	10603522.2	28862.08303	2.563304	10656600.3	16577.11207	10640023.2	4150901.533
25			16941.80853		454.842774	7768.399		1213.678665	10.48354933	15318.21855	10836799.7	29497.04885	2.665836	10891062.33	16941.80853	10874120.5	4079065.316
26			17314.52832		464.849315	7939.303		1256.263881	10.71418741	15655.21935	11075209.2	30145.98393	2.77247	11130681.58	17314.52832	11113367.1	4008471.838
27			17695.44794		475.0759999	8113.968		1298.849097	10.94989953	15999.63418	11318863.9	30809.19557	2.883369	11375571.52	17695.44794	11357876.1	3939099.625
28			18084.7478		485.5276719	8292.475		1341.434313	11.19079732	16351.62613	11567878.9	31486.99788	2.998703	11625848.11	18084.7478	11607763.4	3870927.573
29			18482.61225		496.2092807	8474.91		1384.01953	11.43699486	16711.36191	11822372.2	32179.71183	3.118651	11881629.84	18482.61225	11863147.2	3803934.942
30			18889.22972		507.1258849	8661.358		1426.604746	11.68860875	17079.01187	12082464.4	32887.66549	3.243398	12143037.83	18889.22972	12124148.6	3738101.348
31			19304.79277		518.2826544	8851.908		1469.189962	11.94575814	17454.75013	12348278.6	33611.19413	3.373133	12410195.87	19304.79277	12390891.1	3673406.76
32			19729.49821		529.6848728	9046.65		1511.775179	12.20856482	17838.75463	12619940.7	34350.6404	3.508059	12683230.44	19729.49821	12663500.9	3609831.492
33			20163.54717		541.33794	9245.676		1554.360395	12.47715325	18231.20724	12897579.4	35106.35449	3.648381	12962270.83	20163.54717	12942107.3	3547356.196
34			20607.14521		553.2473746	9449.081		1596.945611	12.75165062	18632.29379	13181326.2	35878.69429	3.794316	13247449.18	20607.14521	13226842	3485961.857
35			21060.50241		565.4188169	9656.961		1639.530828	13.03218693	19042.20426	13471315.3	36668.02556	3.946089	13538900.52	21060.50241	13517840	3425629.79
36			21523.83346		577.8580309	9869.414		1682.116044	13.31889505	19461.13275	13767684.3	37474.72213	4.103933	13836762.84	21523.83346	13815239	3366341.632
37			21997.35779		590.5709075	10086.54		1724.70126	13.61191074	19889.27767	14070573.3	38299.16601	4.26809	14141177.2	21997.35779	14119179.8	3308079.334
38			22481.29967		603.5634675	10308.44		1767.286476	13.91137277	20326.84178	14380125.9	39141.74767	4.438813	14452287.75	22481.29967	14429806.4	3250825.16
39			22975.88826		616.8418638	10535.23		1809.871693	14.21742298	20774.0323	14696488.7	40002.86611	4.616366	14770241.78	22975.88826	14747265.9	3194561.681
40			23481.3578		630.4123848	10767.01	160105.7048	1852.456909	14.53020628	21231.06101	15019811.5	40882.92917	4.801021	15255295.57	23481.3578	15231814.2	3172620.031
41			23997.94767		644.2814573	11003.88		1895.042125	14.84987082	21698.14435	15350247.3	41782.35361	4.993061	15427285.88	23997.94767	15403287.9	3084938.584
42			24525.90252		658.4556493	11245.97		1937.627342	15.17656798	22175.50353	15687952.8	42701.56539	5.192784	15766687.06	24525.90252	15742161.2	3031545.588
43			25065.47238		672.9416736	11493.38		1980.212558	15.51045247	22663.36461	16033087.7	43640.99983	5.400495	16113554.13	25065.47238	16088488.7	2979076.522
44			25616.91277		687.7463904	11746.23		2022.797774	15.85168243	23161.95863	16385815.7	44601.10183	5.616515	16468051.34	25616.91277	16442434.4	2927515.408
45			26180.48485		702.876811	12004.65		2065.382991	16.20041944	23671.52172	16746303.6	45582.32607	5.841176	16830346.56	26180.48485	16804166.1	2876846.544
46			26756.45552		718.3401008	12268.75		2107.968207	16.55682867	24192.2952	17114722.3	46585.13724	6.074823	17200611.33	26756.45552	17173854.9	2827054.5
47			27345.09754		734.1435831	12538.66		2150.553423	16.9210789	24724.52569	17491246.2	47610.01026	6.317816	17579020.99	27345.09754	17551675.9	2778124.11
48			27946.68968		750.2947419	12814.51		2193.138639	17.29334263	25268.46525	17876053.6	48657.43048	6.570528	17965754.72	27946.68968	17937808	2730040.473
49			28561.51686		766.8012262	13096.43		2235.723856	17.67379617	25824.37149	18269326.8	49727.89395	6.833349	18360995.66	28561.51686	18332434.1	2682788.944
50			29189.87023		783.6708532	13384.55		2278.309072	18.06261969	26392.50766	18671252	50821.90762	7.106683	18764930.97	29189.87023	18735741.1	2636355.13
																	190097893.8

Figure 24 – Cost-benefit analysis working using net present value measure

CHAPTER 5. DISCUSSION, LIMITATIONS AND FUTURE RESEARCH

This section reviews the findings of the results section, explains the outliers and presents the scope for future research. This is followed by the conclusion section which summarizes the entire work.

5.1 Discussion

This study analyzed the thermal performance of the green roofs using a simulation study. Though most earlier researches presented outstanding results for energy-savings of green roofs, the energy simulations carried out in this study show contradictory results. Based on the high energy savings figures, most of the previously carried out cost-benefit analysis didn't incorporate other benefits of green roofs. Therefore, in certain studies, green roofs were not able to recover initial installation and maintenance costs, and because of which green roofs were not presented as a profitable measure. This study gives insights into the energy performance of the green roofs when the insulation of the base case is high and follows the mandates of contemporary standards. This study uses constant values for the insulation while varying other green roof parameters to study the behavior of green roofs under high insulation. The four climate zones showed energy savings figures ranging from -0.17-5.77%. The maximum energy savings were experienced by the tropical climate of Atlanta where both the heating and cooling loads are reduced simultaneously. The climates of Chicago and Los Angeles encountered an increase in the cooling load due to high insulation values whereas there was no major change in the cooling load values of Phoenix even though it provided the maximum scope for cooling energy reduction. Chicago underwent the maximum reduction in heating loads but that decrease was countered by the increase in the cooling load. Therefore, a moderate insulation value is required for Chicago which balances the reduction in both heating and cooling. Green roofs were not found a suitable measure from an energy performance perspective for the climate of Los Angeles as they increased the thermal loads of the medium-sized office building. The dry climate of Phoenix can only take advantage of the energy benefit of green roofs for the retrofitting of older buildings where the insulation of the base roof assembly is low. The energy simulations for a roof dominated structure showed that green roofs produced more energy savings for all the climate zones for a higher roof to wall ratio and this effect was more striking for Los Angeles and Chicago.

In the cost-benefit analysis measure, the energy savings benefit provided the least contribution to the total benefits. When it comes to the private benefits accrued to the owner, the increase in the property value due to the aesthetics of this landscaping element provided the maximum financial benefits. However, factors such as inflation rate, discount rate, material, and labor cost, the government provided incentives and other economic policies vary with countries and regions. The costs and benefits reported in Figure 24 show that the benefits of the green roof exceeded its total cost over its life cycle of 50 years by USD 110,528,617. Though single floor study showed improved values of energy savings, this benefit still contributed just 0.36% of the total benefits. Only after considering the comprehensive social and environmental benefits of green roofs, they can be proposed as a sound investment.

Despite the scientific evidence of their ecological benefits, green roofs are not prevailing in the US. A recent survey conducted by Green Roof for Healthy Cities shows 3,112,818 sq ft. of green roof across the North American region which includes the 34 US States and 3 Canadian provinces. This figure was reportedly a drop from the survey figures documented in the year 2017. This conservative estimate can be attributed to limited policy support by the government. The stormwater management benefits taken in this study ranged only from $300-$780 across 50 years because of poor stormwater regulations which are there only in a handful of cities. Similar is the case with other benefits like carbon sequestration and improved air quality. The monetary values of these benefits are based on the potential emission credits and tax discounts that haven't been firmly implemented yet and are still in progress. Apart from this, the financial incentives and building mandates for green roofs, that could promote and provide rewards to private building owners, are very scarcely distributed across different regions. It also needs to be stated that some of the other secondary benefits of green roofs such as urban food production, reduction in landfill cost, improved biodiversity, creation of natural habitat, employment creation, etc. have not been incorporated in this analysis which would have further outweighed the investment costs.

5.2 Limitations

The reference office building model considered in this study was taken from the pool of commercial benchmark models developed by the U.S. Department of Energy (DOE). These models complied with ANSI/ASHRAE/IESNA Standard 90.1-2004 and thus the various envelope parameters such as the R-value of the roof were outdated. The most recent version of ANSI/ASHRAE/IESNA Standard 90.1-2019 recommends a minimum R-value of the insulation value as 5.28 m^2 K/W (Zone-5A) for Chicago and 4.4 m^2 K/W (Zones- 3A, 3B, 2B) for Atlanta, Los Angeles and, Phoenix. Since the R-values of these models were based on an older version of ASHRAE, they were almost half of the newly recommended values. The energy savings are expected to reduce further with the incorporation of new R-values in the model.

5.3 Scope of Future Research

Since this study focuses specifically on the extensive green roof typology, future studies might analyze intensive green roofs with a substrate depth of more than 6 inches, and plant height greater than 50 cm. The results demonstrated in the sensitivity analysis show that plant height is one of the significant factors impacting the energy performance of the green roofs in all the climate zones, though its effect varies across different seasons. The increase of the plant height beyond 50cm would require deeper depths of the growing media and are expected to improve the thermal performance. The scope of the cost-benefit analysis carried out in this study was also limited to the extensive typology. The material, installation, and maintenance cost would increase for intensive green roofs, and thus the net present value will vary accordingly based on the cost and energy savings figure and other range of benefits which it provides.

The current research keeps the insulation value constant to observe how green roofs perform under high prescribed insulation values based on ANSI/ASHRAE/IESNA Standard 90.1-2004. The next steps could involve keeping the insulation values variable in the optimization design variables to obtain an optimal value of the insulation thickness that can maximize energy savings. The results are expected to show low insulation values as the solution for cooling dominated climates (Mahmoodzadeh, Mukhopadhyaya, & Valeo, 2020) (Jaffal, Ouldboukhitine, & Belarbi, 2012) (La Roche & Berardi, 2014) (Castleton H. F., 2010).

Soil moisture content is one of the important characteristics which affect the evapotranspiration rate of the vegetative layer. This moisture content may vary throughout the year depending upon the precipitation amount of the climate zone and irrigation values provided by the user. The thermal properties of the substrate differ for different saturation levels. This study used the soil properties from the previous literature and kept them constant except for the substrate depth. EnergyPlus offers the flexibility to input the user-defined irrigation schedules based on a certain threshold of the current moisture levels. Future studies could explore the rate of irrigation to control the soil moisture levels and thus analyze the effect of varying saturation levels on the energy performance of a green roof. This irrigation schedule will also help in enhancing the accuracy of maintenance costs over the life cycle of a green roof. The irrigation schedule will depend upon the species of the vegetation planted over the green roof.

A few of the benefits considered in this study such as improved air quality and reduction in noise pollution relied upon data from previous studies. Hence, further research needs to be carried out to obtain results relevant to contemporary situations, thus providing more realistic results. In addition, since the estimated benefits were specific to the city of Chicago, the same results of the cost-benefit analysis can not be extended to the other regions. Based on the specific regional incentives and other economic policies, the cost-benefit analysis needs to be carried out for the rest of the climate zones as well.

CHAPTER 6. CONCLUSION

Green Roofs are widely known for their energy efficiency features. This can be supported by the extensive number of researches that have been previously carried out to explore this specific benefit of a green roof. But most of this literature lacks consistency in the results due to the difference in the experimental and simulation settings. There are several factors such as climate, roof shape, insulation thickness, roof-envelope ratio, and other component layer parameters that affect the thermal performance of a green roof. This thesis provides an insight into the role of insulation thickness in influencing the energy savings potential of green roofs. It presents the feasibility of the green roofs in four climate zones of the U.S. by performing a series of energy simulations on the commercial benchmark buildings developed by the U.S. DOE. For the scenario of multistorey reference buildings, the humid subtropical climate of Atlanta is the near-optimal climate for achieving maximum energy savings. Whereas, for single storey structures, the reduction in heating loads by the green roofs is substantial, which makes it conducive for the heating-dominated climates. This thesis also suggests that the design of green roof parameters such as LAI, plant height, leaf reflectivity, leaf emissivity, soil depth, and minimum stomatal resistance is crucial for the thermal performance of a green roof, and the effect of these parameters varies across different climates and seasons. The cost-benefit analysis of green roofs shows that even though energy savings of green roofs are insignificant, private owners can benefit to a great extent from government incentives and increased rental rates of the property. Apart from this, other environmental and social benefits of green roofs such as improved air quality, carbon sequestration, reduction in noise pollution, and urban heat island provide significant capital benefits to the society as a whole and justify the incorporation of green roofs in our built environments. Thus, a green roof, with its unique characteristics, serves as a net-positive strategy for adapting to the impacts of climate change, and for making more livable communities.

APPENDIX A. OPTIMIZATION SETTINGS AND SYNTAX USED IN GENOPT

This appendix illustrates the format of various text-based input files required for the initialization of GenOpt using figure representation. These figures demonstrate the settings and syntax that were adhered to for a successful optimization run.

Figure 25 represents the changes that need to be incorporated in the RoofVegetation section of the IDF file to convert it into a template that can take the assumed values of the design variables in the specified range.

```
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:ROOFVEGETATION ===========

Material:RoofVegetation,
    GreenRoof,                !- Name
    %Height%,                 !- Height of Plants {m}
    %LAI%,                    !- Leaf Area Index {dimensionless}
    %LeafRfl%,                !- Leaf Reflectivity {dimensionless}
    %LeafEmsvt%,              !- Leaf Emissivity
    %Stml%,                   !- Minimum Stomatal Resistance {s/m}
    Green Roof Soil,          !- Soil Layer Name
    MediumRough,              !- Roughness
    %SoilDepth%,              !- Thickness {m}
    0.35,                     !- Conductivity of Dry Soil {W/m-K}
    1100,                     !- Density of Dry Soil {kg/m3}
    1200,                     !- Specific Heat of Dry Soil {J/kg-K}
    0.9,                      !- Thermal Absorptance
    0.7,                      !- Solar Absorptance
    0.75,                     !- Visible Absorptance
    0.3,                      !- Saturation Volumetric Moisture Content of the Soil Layer
    0.01,                     !- Residual Volumetric Moisture Content of the Soil Layer
    0.1,                      !- Initial Volumetric Moisture Content of the Soil Layer
    Advanced;                 !- Moisture Diffusion Calculation Method
```

Figure 25 - Input template file in which the design parameters from the command file are written.

```
Vary{
    Parameter{  //Leaf Area Index
    Name    = LAI;
    Min     = 0.001;
    Ini     = 1;
    Max     = 5.0;
    Step    = 1;
    }
    Parameter{  //Height of Plants
    Name    = Height;
    Ini     = 0.1;
    Step    = 0.1;
    Min     = 0.05;
    Max     = 0.5;
    Type    = CONTINUOUS;
    }
    Parameter{  //Leaf Reflectivity
    Name    = LeafRfl;
    Ini     = 0.1;
    Step    = 0.1;
    Min     = 0.1;
    Max     = 0.4;
    Type    = CONTINUOUS;
    }
    Parameter{   //Leaf Emissivity
    Name    = LeafEmsvt;
    Ini     = 0.8;
    Step    = 0.05;
    Min     = 0.8;
    Max     = 1;
    Type    = CONTINUOUS;
    }
    Parameter{   // Minimum Stomatal Resistance
    Name    = Stml;
    Min     = 50;
    Ini     = 60;
    Max     = 300;
    Step    = 40;
    }
    Parameter{   // Thickness
    Name    = SoilDepth;
    Min     = 0.1;
    Ini     = 0.1;
    Max     = 0.3;
    Step    = 0.1;
    }
}
```

Figure 26 - Syntax for specifying the design variables with their constraints in the command file

Figure 26 illustrates the design variables that are specified in the command file of GenOpt. The constraints applied to each variable are specified in this file using minimum, maximum, and step values. It also shows whether the variable is continuous or discrete.

```
OptimizationSettings{
  MaxIte = 4000;
  MaxEqualResults = 100;
  WriteStepNumber = false;
  UnitsOfExecution = 0;
}

Algorithm{
  Main = GPSPSOCCHJ;
  NeighborhoodTopology = vonNeumann;
  NeighborhoodSize = 20;
  NumberOfParticle = 36;
  NumberOfGeneration = 1000;
  Seed = 0;
  CognitiveAcceleration = 2.8;
  SocialAcceleration = 1.3;
  MaxVelocityGainContinuous = 0;
  MaxVelocityDiscrete = 4;
  ConstrictionGain = 1;
  MeshSizeDivider = 2;
  InitialMeshSizeExponent = 0;
  MeshSizeExponentIncrement = 1;
  NumberOfStepReduction = 4;
}
```

Figure 27 - Syntax for writing the selected optimization algorithm and specifying its settings in the command file.

Figure 27 shows the selection of an appropriate optimization algorithm, GPSPSOCCHJ, which is the representation of the hybrid algorithm of PSO and Hookes-Jeeve algorithm. It also shows the stopping criteria to end the iteration by specifying the maximum number of iterations. The different settings relevant to the hybrid algorithm can also be seen in the figure.

Figure 28 shows the syntax for specifying the formulated objective function in the initialization file. The values of the variables mentioned in the objective function are read from the output file of EnergPlus. For picking up the correct values from the output file, delimiter values are specified based on the location of the values of each variable.

```
ObjectiveFunctionLocation
{
    Name1      = Es_tot;
    Function1  = "add( %Es_heat%, %Es_cool%, %Es_heatGas%)";

    Name2      = Es_heat;
    Function2  = "divide( %Q_heat%, 0.44)";

    Name3      = Es_cool;
    Function3  = "divide( %Q_cool%, 0.77)";

    Name4      = Es_heatGas;
    Function4  = "divide( %Q_Gas%, 0.8)";

    Name5             = Q_heat;
    Delimiter5        = "1530,";
    FirstCharacterAt5 = 1;

    Name6             = Q_cool;
    Delimiter6        = "1656,";
    FirstCharacterAt6 = 1;

    Name7             = Q_Gas;
    Delimiter7        = "1580,";
    FirstCharacterAt7 = 1;
 }
```

Figure 28 - Syntax for specifying the objective function with its variables which are read from the EnergyPlus output file.

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